ECONOMIC GEOLOGY

VOL. XXXVII AUGUST, 1942 No. 5

# PROGRESS IN THE STUDY OF EXSOLUTION IN ORE MINERALS.

G. M. SCHWARTZ.

ABSTRACT.

A review of the literature shows that at least 50 pairs of minerals exhibit textures which have suggested to various investigators that exsolution has occurred during their formation. The list of criteria suggested in 1931 is revised and amplified. A decade of work seems to justify the criteria but more critical evaluation is still needed.

## INTRODUCTION.

IN 1931 the writer published a review [1] of textures due to unmixing (exsolution) in ore minerals. This review included papers published through 1930. Over ten years of work and progress is represented by papers published since 1931. It seems desirable to briefly review the situation and evaluate the progress that has been made in the knowledge of these textures in the ore minerals.

The term exsolution has grown in favor in recent years and is now largely used in place of other suggested terms for both the process and the texture. It would perhaps be well to make this usage more nearly universal, but unmixing is firmly entrenched in the literature and is a literal translation of the German term (entmischung) so its use will probably be difficult to avoid. Perhaps there is no great harm in using unmixing and exsolution interchangeably.

## LIST OF MINERALS EXHIBITING EXSOLUTION.

Following is a list of minerals which have been described by various authors as exhibiting exsolution. The host mineral is listed first. Where each may act as the host an asterisk indicates this fact. Some examples are questionable. Where there is serious doubt a question mark is used.

[1] Schwartz, G. M.: Textures due to unmixing of solid solutions. ECON. GEOL., 26: 739–763, 1931.

| | |
|---|---|
| 1. Alabandite—pyrrhotite | $MnS—FeS_{1+}$ |
| 2. Bismuthinite—argentite | $Bi_2S_3—Ag_2S$ |
| 3. Bismuthinite—emplectite | $Bi_2S_3—Cu_2S.Bi_2S_3$ |
| 4. Bornite—chalcocite | $Cu_5FeS_4—Cu_2S$ |
| 5. Bornite—chalcopyrite* | $Cu_5FeS_4—CuFeS_2$ |
| 6. Bornite—klaprotholite | $Cu_5FeS_4—3Cu_2S.2Bi_2S_3$ |
| 7. Bornite—linnaeite | $Cu_5FeS_4—CO_3S_4$ |
| 8. Cassiterite—tantalite | $SnO_2—(Fe, Mn)Ta_2O_6$ |
| 9. Chalcocite—covellite | $Cu_2S—CuS$ |
| 10. Chalcocite—stromeyerite | $Cu_2S—Cu_2S.Ag_2S$ |
| 11. Chalcopyrite—cubanite* | $CuFeS_2—Cu_2S.Fe_4S_5$ |
| 12. Chalcopyrite—vallerite | $CuFeS_2—Cu_2Fe_4S_7$ |
| 13. Chalcopyrite—pyrrhotite | $CuFeS_2—FeS_{1+}$ |
| 14. Chromite—hematite | $FeO.Cr_2O_3—Fe_2O_3$ |
| 15. Chromite—ilmenite | $FeO.Cr_2O_3—FeO.TiO_2$ |
| 16. Corundum—hematite | $Al_2O_3—Fe_2O_3$ |
| 17. Cosalite—brongniardite | $2PbS.Bi_2S_3—$ |
| 18. Cubanite—pyrrhotite | $Cu_2S.Fe_4S_5—FeS_{1+}$ |
| 19. Famatinite—chalcocite | $Cu_2S.4CuS.Sb_2S_3—Cu_2S$ |
| 20. Galena—argentite | $PbS—Ag_2S$ |
| 21. Galena—pyrargyrite | $PbS—3Ag_2S.Sb_2S_3$ |
| 22. Galena—tetrahedrite | $PbS—5Cu_2S.2(CuFe)S.2Sb_2S_3$ |
| 23. Galena—stromeyerite ? | $PbS—Cu_2S.Ag_2S$ |
| 24. Hematite—rutile* | $Fe_2O_3—TiO_2$ |
| 25. Ilmenite—hematite* | $FeO.TiO_2—Fe_2O_3$ |
| 26. Ilmenite—pyrophanite | $FeO.TiO_2—MnO.TiO_2$ |
| 27. Ilmenite—hematite—rutile | $FeO.TiO_2—Fe_2O_3—TiO_2$ |
| 28. Jacobsite—hausmannite | $MnO.Fe_2O_3—MnO.Mn_2O_3$ |
| 29. Linnaeite—millerite | $Co_3S_4—NiS$ |
| 30. Magnetite—hematite | $FeO.Fe_2O_3—Fe_2O_3$ |
| 31. Magnetite—ilmenite* | $FeO.Fe_2O_3—FeO.TiO_2$ |
| 32. Magnetite—pyrophanite | $FeO.Fe_2O_3—MnO.TiO_2$ |
| 33. Magnetite—rutile | $FeO.Fe_2O_3—TiO_2$ |
| 34. Magnetite—spinel | $FeO.Fe_2O_3—MgO.Fe_2O_3$ |
| 35. Manganosite—zincite | $MnO—ZnO$ |
| 36. Periclase—manganosite | $MgO—MnO$ |
| 37. Platinum—iridium | $Pt—Ir$ |
| 38. Pyrrhotite—pentlandite* | $FeS_{1+}—(Fe, Ni)S$ |
| 39. Silver—dyscrasite | $Ag—Ag_3Sb$ |
| 40. Sphalerite—chalcopyrite | $ZnS—CuFeS_2$ |
| 41. Sphalerite—pyrite | $ZnS—FeS_2$ |
| 42. Sphalerite—pyrrhotite | $ZnS—FeS_{1+}$ |
| 43. Stannite—chalcopyrite | $Cu_2S.FeS.SnS_2—CuFeS_2$ |
| 44. Stannite—cubanite | $Cu_2S.FeS.SnS_2—Cu_2S.Fe_4S_5$ |
| 45. Stannite—pyrite | $Cu_2S.FeS.SnS_2—FeS_2$ |
| 46. Stannite—sphalerite* | $Cu_2S.FeS.SnS_2—ZnS$ |
| 47. Stannite—tetrahedrite | $Cu_2S.FeS.SnS_2—5Cu_2S.2(CuFe)S, 2Sb_2S_3$ |
| 48. Stromeyerite—argentite (?) | $Cu_2S.Ag_2S—Ag_2S$ |
| 49. Tantalo-rutile—ilmenite | $TiO_2(FeO.Ta_2O_5)—FeO.TiO_2$ |
| 50. Tennantite—chalcopyrite | $5Cu_2S.2(CuFe)S.2As_2S_3—CuFeS_2$ |
| 51. Tennantite—galena ? | $5Cu_2S.2(CuFe)S.2As_2S_3—PbS$ |

SUMMARY OF DATA.

*Alabandite-Pyrrhotite.* A Bolivian specimen of alabandite is described by Schneiderhöhn and Ramdohr [2] as containing small idiomorphic grains of pyrrhotite arranged along the (111) planes of the alabandite. These inclusions are assigned to a probable origin by exsolution.

*Bismuthinite-Argentite.* In 1931 the writer expressed the opinion that some so called lillianite from Leadville which had been shown to be an intergrowth of bismuthinite and argentite was a result of exsolution. Little further data are available except that so called lillianite from other regions has been shown to consist of galeno-bismutite and galena. This is referred to below.

*Bismuthinite-Emplectite.* Ramdohr [3] has referred lattice intergrowths of bismuthinite and emplectite from the Bleka mine, Norway, to a probable origin by exsolution.

*Bornite-Chalcocite.* The complicated relations of bornite have been the subject of much study. Experimental work proving solid solution and exsolution of bornite and chalcocite were reviewed in the 1931 summary. Recently the writer [4] attempted a classification of the microtextures exhibited by these minerals. Thirteen textures with some subtypes were recognized. Of these at least three are probably a result of exsolution. Stephens [5] has contributed to the identification of types of chalcocite including those involved in exsolution textures. An excellent example of the value of the interpretation of exsolution intergrowths is given by Bateman [6] in a study of the Rhodesion copper ores where the

[2] Schneiderhöhn, H., and Ramdohr, P.: Lehrbuch der Erzmikroskopie. Berlin, 1931, p. 101.

[3] Ramdohr, P.: Neue Beobachtungen über die Verwendbarkeit opaker Erze als 'geologische Thermometer.' Zeit. Prak. Geol., 39: 70, 1931.

[4] Schwartz, G. M.: Significance of bornite-chalcocite microtextures. ECON. GEOL., 36: 399–418, 1939.

[5] Stephens, M. M.: The identification of types of chalcocite by the use of the carbon arc. ECON. GEOL., 30: 604–629, 1935.

[6] Bateman, A. M.: The ores of Northern Rhodesian copper belt. ECON. GEOL., 25: 365–418, 1930.

conclusion that chalcocite is hypogene is partly based on the evidence of exsolution intergrowths. Schneiderhöhn and Ramdohr [7] describe and discuss the origin of bornite-chalcocite intergrowths in considerable detail and refer several to an origin by exsolution.

*Bornite-Chalcopyrite.* Experiments reported by the writer [8] showed conclusively that solid solutions of each in the other exist above 475° C. and exsolve on cooling. Only intergrowths representing the bornite end are common. Schneiderhöhn and Ramdohr [9] illustrate excellent examples from Katanga, from Germany and from Sweden. Additional examples with a bornite host have been described since 1931 by Haley,[10] by Edwards,[11] by Scholtz,[12] and by Schouten.[13] Schouten also produced a lattice intergrowth by diffusion from hot (120° C.) solutions. This raises the question if replacement of this type may not be a complicated process involving the formation of a solid solution by diffusion at elevated temperatures with subsequent exsolution on cooling. In other words replacement and exsolution are not of necessity mutually exclusive.

*Bornite-Klaprotholite.* Krieger [14] has described a varied series of inclusions of klaprotholite in bornite and concluded that some of the more definitely crystallographic types resulted from exsolution. A similar example is referred to by Watanabe.[15] The

[7] Op. cit., pp. 338–340.

[8] Schwartz, G. M.: Intergrowths of bornite and chalcopyrite. ECON. GEOL., 20: 186–201, 1931.

[9] Op. cit., p. 338.

[10] Haley, A. J.: Geology of Campana, Chile. Master's Thesis, 1938, University of Minnesota.

[11] Edwards, A. B.: Some observations on the mineral composition of the Mt. Lyell copper ores, Tasmania. Austral. Inst. Min. Met. Proc. n.s., 114: 67–109, 1939.

[12] Scholtz, D. L.: The magmatic nickeliferous ore deposits of East Griqualand and Pondoland. Geol. Soc. S. Africa, Trans., 39: 82–119, 1936.

[13] Schouten, I. C.: Metasomatische Probleme, Amsterdam, 1937.

———: Structures and textures of synthetic replacements. ECON. GEOL., 29: 611–658, 1934.

[14] Krieger, P.: Bornite-klaprotholite relations at Conception del Oro, Mexico. ECON. GEOL., 35: 387, 1940.

[15] Watanabe, M.: Annot. Bib. Econ. Geol. 11, No. 1: 209, p. 32, 1939.

analogy of the texture with that of chalcopyrite in bornite strongly suggests an origin by exsolution.

*Bornite-Linnæite.* Edwards [16] has illustrated lamallæ or rods of linnæite in bornite which may well be a result of exsolution although he does not express this opinion except as it may be implied in the use of the term lamellæ to describe the inclusions.

*Cassiterite-Tantalite.* Edwards [17] came to the conclusion that cassiterite is capable of forming a solid solution at high temperatures with tantalite or tapiolite, and that at lower temperatures the tantalum molecule is precipitated either as tapiolite or tantalite and migrates to the grain boundaries of the cassiterite.

*Chalcocite-Covellite.* Bateman and Lasky [18] made an exhaustive restudy of the relation of covellite and chalcocite. Covellite was shown to be soluble in chalcocite but little if any chalcocite is soluble in covellite. Exsolution occurs in a narrow range below 70° C. with covellite segregating along the parting planes of the chalcocite. The hypogene origin of the Kennecott covellite is thus considered as proven. Intergrowths of covellite in orthorhombic chalcocite indicate an origin between 70° and 93° C.

*Chalcocite-Stromeyerite.* It has been suggested that natural intergrowths of stromeyerite in chalcocite result from exsolution. Working partially with synthetic material, the writer [19] has shown that stromeyerite forms by exsolution from a solid solution of $Cu_2S$ and $Ag_2S$. Above 300° C. a uniform sulphide exists which on cooling exsolves blades of stromeyerite. The greater the excess of $Cu_2S$ the better the blades of stromeyerite.

*Chalcopyrite-Cubanite.* The exsolution of cubanite from chalcopyrite was one of the first to be worked out experimentally. Many examples of these intergrowths have been described in

[16] Op. cit., p. 97.

[17] Edwards, A. B.: A note on some tantalum-niobium minerals from Western Australia. Austral. Inst. Min. Met. Proc., n.s., 120: 731–794, 1940.

[18] Bateman, A. M., and Lasky, S. G.: Covellite-chalcocite solid solution and exsolution. ECON. GEOL., 27: 52–86, 1932.

[19] Schwartz, G. M.: Chalcocite-stromeyerite-argentite. ECON. GEOL., 30: 138–146, 1935.

recent years, notably from Sudbury,[20] South Africa,[21] Schneeberg,[22] and Oregon.[23]

The crystallography of the cubanite intergrowths has been treated in some detail by N. W. and M. S. Buerger.[24] The importance of twinning is emphasized and it is suggested that exsolution of cubanite may have been the cause of the stresses which produced the twinning.

*Chalcopyrite-Pyrrhotite.* Borchert [25] found in his experiments that pyrrhotite slowly dissolved in chalcopyrite forming an intergrowth essentially like that formed by exsolution. Pyrrhotite and chalcopyrite at certain ranges of temperature may be accompanied by other minerals such as cubanite. Chalcopyrrhotite on cooling decomposes between 255° and 235° C. into chalcopyrite and pyrrhotite.

Stevenson [26] described curving hair-like areas and wisps or vermicules of pyrrhotite in chalcopyrite. These occur singly or as three radiating from a center. The pyrrhotite vermicules are single crystals unlike veins which consist of many units. The conclusion is reached that the pyrrhotite probably resulted from unmixing.

*Chalcopyrite-Vallerite.* Borchert [27] has made a detailed study of the complex series of exsolution products in the system Cu-Fe-S. Vallerite occurring as inclusions in chalcopyrite was found to

[20] Newhouse, W. H.: A pyrrhotite-cubanite-chalcopyrite intergrowth from the Frood mine, Sudbury. Am. Min., 16: 334–337, 1931.

[21] Scholtz, D. L.: The magmatic nickeliferous ore deposits of East Griqualand and Pondoland. Geol. Soc. S. Africa, Trans., 39: 82–198, 1936.

[22] Eberhard, C.: Zwei erzentmischungen von Schneeberg in Tirol. Centr. Min. Abt. A (5): 147–153, 1931.

[23] Shenon, P. J.: A massive sulphide deposit of hydrothermal origin in serpentine. Econ. Geol., 27: 597–613, 1932.

[24] Buerger, N. W. and Buerger, M. S.: Crystallographic relations between segregation plates, chalcopyrite matrix, and secondary chalcopyrite twins. Am. Min., 19: 289–303, 1930.

[25] Borchert, H.: Über entmischungen im System Cu-Fe-S und ihre Bedeutung als "geologische Thermometer." Chem. der Erde, 9: 145–172, 1934.

[26] Stevenson, J. S.: Vein-like masses of pyrrhotite in chalcopyrite from the Waite-Ackerman-Montgomery mine, Quebec. Am. Min., 18: 445–449, 1933.

[27] Op. cit., p. 148.

be stable only to 225° C., above which it breaks down with the CuS diffusing into the chalcopyrite and pyrrhotite remains. Buerger [28] has described vallerite which forms minute crosses of unvarying orientation in chalcopyrite. These he believes to have formed by exsolution. Scholtz [29] described vallerite in chalcopyrite and pentlandite from Insizwa, but found no evidence of exsolution.

*Chromite-Ilmenite.* Ramdohr [30] discovered ilmenite intergrown in chromite and believes the texture a result of exsolution. His microphotograph shows a very diagrammatic lattice of ilmenite in chromite corresponding with what one might call a typical exsolution texture.

*Chromite-Hematite.* Ramdohr [31] has also referred to exsolution chromite-hematite intergrowths in chromite ore from the Bushveldt.

*Corundum-Hematite.* Bray [32] found minute hematite blebs included in corundum from the island of Naxos which he suggests are a result of exsolution. The blebs are concentrated as swarms toward the center of subhexagonal corundum grains. Some blebs exhibit a roughly hexagonal outline. A similar example is described from Whittier, Virginia.

*Cosalite-Brongniardite.* Anderson [33] illustrates brongniardite forming a triangle lattice or grating structure in cosalite and shows that the characteristics of the texture correspond with the tentative criteria proposed in 1931 for origin by exsolution. All of the pseudo-eutectic textures described on the other hand are believed to have formed by replacement.

[28] Buerger, N. W.: Cooper ores of Orange County, Vermont. ECON. GEOL., 30: 439–443, 1935.

[29] Op. cit., p. 72.

[30] Ramdohr, P.: Die Erzmineralien in gewöhnlichen magmatischen Gesteinen. Ab. der Preus. Ak. der Wiss. Jahrgang, 1940, pp. 1–43.

[31] Ramdohr, P.: Neue Beobachtungen über die Verwendbarkeit opaker Erze als "geologische Thermometer." Zeit. Prak. Geol., 39: 90, 1931.

[32] Bray, J. M.: Ilmenite-hematite-magnetite relations in some emery ores. Am. Min., 24: 162–170, 1930.

[33] Anderson, A. L.: Some pseudo-eutectic textures. ECON. GEOL., 29: 577–589, 1934.

*Cubanite-Pyrrhotite.* In the complex intergrowths of pyrrhotite-cubanite-chalcopyrite described by Newhouse [34] from the Frood mine, Sudbury, pyrhotite occurs as two sets of intersecting blades in areas which are mainly cubanite with minute laths of chalcopyrite. Lath-shaped masses of cubanite have pyrrhotite as two sets of blades which end abruptly at the contact with chalcopyrite. An essentially similar example is shown from Kaveltorp, Sweden, by Schneiderhöhn and Ramdohr.[35]

*Famatinite-Chalcocite.* Natural specimens of this combination have not been described to the writer's knowledge, but Gaudin and Dicke [36] found chalcocite precipitated along crystallographic directions in famatinite in synthetic preparations involving sulphide compounds.

*Galena-Argentite.* In 1931 examples of suggested exsolution of argentite from galena were mentioned but the inconclusive nature of the examples was noted. This deficiency is removed by the examples described by Schneiderhöhn and Ramdohr.[37]

*Galena-Pyrargyrite.* The above authors also refer to many galena specimens which contain inclusions of pyrargyrite evidently a result of exsolution.

*Galena-Tetrahedrite.* Originally suggested by R a m d o h r. Oelsner [38] shows minute inclusions of tetrahedrite in galena which he assigns to unmixing.

*Galena-Stromeyerite.* Galena and stromeyerite are found as graphic (pseudo-eutectic) intergrowths. No direct evidence has ever shown that such intergrowths in ore minerals result from exsolution. Much evidence has been presented to show that they often result from replacement.

[34] Op. cit., p. 335.

[35] Op. cit., p. 365.

[36] Gaudin, A. M., and Dicke, G.: The pyrosynthesis, microscopic study and iridescent filming of sulphide compounds with arsenic, antimony and tin. ECON. GEOL., 34: 49–81, 1939.

[37] Op. cit., pp. 242–262.

[38] Oelsner, O.: Beitrage zur Kenntnis der kiesigen Bleierzformation Freibergs. Dissertation, Freiberg, 1929.

*Hematite-Rutile.* Newhouse [39] shows rutile as intergrowths in hematite. The texture is characteristic of exsolution. These occur in granites, syenites and anorthosites.

*Ilmenite-Hematite.* Ramdohr [40] proved that hematite dissolved in ilmenite, and suggested that two sets of lamellæ often observed were a result of a change in symmetry as well as ordinary solubility. Greig [41] has shown that some of Ramdohr's conclusions do not necessarily follow from his experimental work. Later studies show that hematite as thin tabular grains parallel to the base is a feature of many ilmenites, such as in deposits at St. Urbain [42] and also at Saint Agathe,[43] Quebec. Bray [44] has recently described several examples. In emery from Naxos ilmenite occurs as minute lamellæ parallel to (0001) and also at borders of crystals. In the emery from Chester, Mass., Bray recognized two types of ilmenite lamellæ in hematite which he believed to be of two generations. In ore from Peekskill, New York, intergrowths of ilmenite and hematite in each other were recognized.

Edwards [45] has given detailed study to ilmenite microstructures. He recognized two kinds of ilmenite; a brown which has a very small amount of $Fe_2O_3$ in solution, and a white which is hematite with up to 10 per cent $TiO_2$ in solution. He suggests the name titanhematite for the latter. If the $TiO_2$ is greater than 10 per cent, lens or disc-shaped bodies of hematite occur in the titan-

[39] Newhouse, W. H.: Opaque oxides and sulphides in common igneous rocks. G. S. A. Bull., 47; pl. 11, 1936.

[40] Ramdohr, P.: Beobachtungen an Magnetit, Ilmenit, Eisenglanz und überlegungen über das system $FeO$-$Fe_2O_3$.$TiO_2$. N. Jahrb. f. Min. Beil., Bd. 54: 320–379, 1926.

[41] Greig, J. W.: Temperature of formation of the ilmenite of the Engels copper deposits. Econ. Geol., 27: 25–38, 1932.

[42] Gillson, J. L.: Genesis of the ilmenite deposits of St. Urbain, County Charlevoix, Quebec. Econ. Geol., 27: 534–577, 1932.

[43] Osborne, F. F.: Saint Agathe-Saint Jovite Map Area. Quebec Bur. Mines, Ann. Rept., Pt. C, 1935, 53–88, 1936.

[44] Bray, J. M.: Ilmenite-hematite-magnetite relations in some emery ores. Am. Min., 24: 162–170, 1939.

[45] Edwards, A. B.: Some ilmenite microstructures and their interpretation. Austral. Inst. Min. Met., Proc., n.s., 110: 39–58, 1938.

hematite. If the $Fe_2O_3$ content of hematite exceeds 6 per cent small bodies of titanhematite appear in ilmenite. There are thus two solid solutions, one rich in $Fe_2O_3$ and one in $FeTiO_3$. The size of lamellae is related to the rate of temperature decrease and to the original composition. Manganilmenite also contains exsolution inclusions of hematite according to Edwards. Intergrowths of ilmenite in hematite are not so numerous but were noted by Edwards.

Posnjak and Barth [46] have investigated the system $Fe_2O_3$-$TiO_2$ and show that solid solutions form readily at 1200 and homogeneous ilmenite and a solid solution midway between hematite and ilmenite were prepared without difficulty. Newhouse [47] found ilmenite-hematite common in the opaque minerals of granites, norites and anorthosites. Norites are distinct from the gabbros in this respect. The problem of exsolution involving ilmenite is summarized by Schneiderhöhn and Ramdohr.[48]

*Ilmenite-Hematite-Rutile.* Edwards has described specimens from Australia as follows, "One consists of an exsolution intergrowth of minute bodies of ilmenite in a base of titanhematite which is criss-crossed by fine lamellae and rutile." There can be little doubt that the development of the rutile preceded the unmixing of the titanhematite. Heating of one of the specimens to 880° C. dissolved most of the ilmenite, but the rutile remained. Newhouse [49] shows a hematite-rutile intergrowth as noted above.

*Jacobsite-Hausmannite.* Johannsson [50] was perhaps the first to point out that some so called jacobsite was an intergrowth of jacobsite and hausmannite. In 1931 Schneiderhöhn and Ramdohr [51] and Orcel and Pavlovitch [52] independently described so

[46] Posnjak, E., and Barth, T. F. W.: Zeit. Krist., 88: 271–280, 1934.

[47] Newhouse, W. H.: Opaque oxides and sulphides in common igneous rocks. G. S. A. Bull., 47: 1–52, 1936.

[48] Op. cit., p. 543.

[49] Op. cit., pl. 11.

[50] Johannson, K.: Mineralogische Mitteilungen. Z. Krist., 68: 107–118, 1928.

[51] Op. cit., p. 602.

[52] Orcel, J., and Pavlovitch, S. T.: Les caracteres microscopiques des oxydes de manganese et des manganites naturels. Bull. de la Soc. Franc. de Mineralogie Nos. 5–8: 108–179, 1931.

called vredenburgite as a lamellar intergrowth of hausmannite in a groundmass of jacobsite. The texture is practically identical with that of ilmenite in magnetite as might be expected since both jacobsite and magnetite belong to the spinel group with parting along the octahedral planes.

*Linnæite-Millerite.* Schneiderhöhn and Ramdohr [53] show an excellent example of a network of millerite lamellæ along the crystallographic planes of linnæite from Wissen, Germany. They logically assign the texture to an origin by exsolution (entmischungen).

*Magnetite-Hematite.* There has been considerable argument as to the mutual solubility of the oxides of iron. Most natural specimens with hematite along the octahedral planes of magnetite are rather clearly a result of partial replacement, *i.e.,* martization. In iron ore sinter the writer [54] has described a possible exsolution intergrowth of hematite along the octahedral planes of magnetite. Work at the Geophysical Laboratory has since shown that $Fe_2O_3$ and $Fe_3O_4$ form solid solutions at high temperature (1075° C.) and on slow cooling exsolution results.[55] Newhouse [56] considers that hematite lamellæ along the octahedral planes of magnetite found in basalt from Mt. Etna originated by exsolution. This is the only natural occurrence of which the writer is aware.

*Magnetite-Ilmenite.* The relations of magnetite and ilmenite as exsolution intergrowths have probably been more carefully described than any other examples. They were reviewed in some detail in 1931. Since then contributions have been made by many investigators. Donnay [57] in 1930 discussed the planes along which ilmenite is oriented and noted that the directions may vary from four in the single crystal of magnetite to seven in dual

[53] Op. cit., Fig. 170.

[54] Schwartz, G. M.: Iron ore sinter. A. I. M. E. Tech. Pap. 227, p. 17, 1929.

[55] Greig and others: Equilibrium relationships of $Fe_3O_4$, $Fe_2O_3$, and oxygen. Am. Jour. Sci., 30: 239–316, 1935.

[56] Op. cit., Fig. 2.

[57] Donnay, J. D. H.: Genesis of the Engels copper deposit. Cong. Intern. des Mines, 6th Ser. Liege, June 1930, 99–111.

twinned crystals, and ten, thirteen and sixteen in complex twinning. Not all directions may be exposed on a single polished surface and not all planes are necessarily occupied by ilmenite. Edwards [58] reviewed the data on magnetite-ilmenite and added examples from Australia. It is shown that magnetite from Mt. Jaggad, South Australia, contains only .01 per cent of $TiO_2$ in solution, but nevertheless contains blebs of ilmenite. In short, if cooling is slow enough, $TiO_2$ is almost entirely thrown out of magnetite as ilmenite. In lava flows which cool rapidly a homogeneous titaniferous magnetite may continue to exist as a solid solution. The completeness of exsolution as well as the rate, is believed to be greater in the case of magnetite-ilmenite than in hematite-ilmenite because the temperature is higher in the former. The ilmenite tends also to aggregate into grains at the margins of the magnetite crystals. Newhouse [59] has shown that magnetite with intergrown ilmenite is a common constituent of most igneous rocks. The prevalence of the intergrowths is noted for each of the principal groups. Faessler and Schwartz [60] describe an unusual type of exsolution intergrowth of ilmenite in magnetite with the ilmenite lamellæ arranged en echelon and mainly along one direction. It is inferred that slipping or translation took place in the magnetite previous to exsolution.

*Magnetite-Pyrophanite.* Schneiderhöhn and Ramdohr [61] report that pyrophanite as tablets parallel to (0001) occurs along the (111) planes of magnetite from Cerro Iman, Uruguay.

*Magnetite-Rutile.* Rutile is at places abundant in ilmenite deposits, for example those at St. Urbain, Quebec, and of the Appalachian area in the United States. Rutile does not commonly form intergrowths with magnetite but Newhouse [62] refers to four examples in granites and syenites.

[58] Edwards, A. B.: Some ilmenite microstructures and their interpretation. Austral. Inst. Min. Met. Proc., n.s., 110: 39–58, 1938.

[59] Op. cit.

[60] Faessler, C. and Schwartz, G. M.: Titaniferous magnetite deposits of Sept Isles, Quebec. Econ. Geol., 36: 712–728, 1941.

[61] Op. cit., p. 581.

[62] Op. cit., Plate 18.

*Magnetite-Spinel.* In 1925 Ramdohr showed that spinel will dissolve in magnetite at 1000° C. and exsolves at about 800°. Newhouse refers to several examples of exsolution spinel in magnetite of igneous rocks. Spinel as microscopic grains and crystals is abundant in some specimens from the Sept-Isles deposits of Quebec. Ramdohr [63] in 1940 illustrated an excellent example of exsolution type of intergrowths of spinel in magnetite from a diabase.

*Manganosite-Zincite.* Frondel [64] has described manganosite with octahedral parting surfaces covered with a more or less continuous film or plate of zincite. He believes that the nature of the intergrowth excludes an origin except by exsolution. The coincidence of the crystal structure of the two minerals is emphasized.

*Periclase-Manganosite.* Frondel found cleavage fragments of periclase from Sweden which contained hosts of minute octahedra of manganosite and believes these to have formed by exsolution.

*Platinum-Iridium.* Schneiderhöhn and Ramdohr [65] show an excellent intergrowth of iridium in platinum which is assigned to an origin by exsolution.

*Pyrrhotite-Pentlandite.* Pyrrhotite and pentlandite have been known to unmix since the early studies of polished surfaces and experimental work by Newhouse [66] threw considerable light on the exact relations. More recently Hewitt [67] reported a series of experiments showing that pentlandite dissolves in pyrrhotite above 425° C. On slow cooling the pentlandite exsolves and segregates to grain boundaries. At the same time the pentlandite grains may contain pyrrhotite laths forming a rather typical exsolution tex-

[63] Ramdohr, P.: Die Erzmineralien in gewöhnlichen magmatischen Gesteinen. Ab. der Preuss. Ak. Wissenschaften, Jarhg., 1940.

[64] Frondel, C.: Exsolution growths of zincite in manganosite and of manganosite in periclase. Am. Min., 25: 534–538, 1940.

[65] Op. cit., p. 45.

[66] Newhouse, W. H.: The equilibrium diagram of pyrrhotite and pentlandite and their relations to natural occurrence. Econ. Geol., 22: 288–299, 1927.

[67] Hewitt, R. L.: Experiments bearing on the relation of pyrrhotite to other sulphides. Econ. Geol., 23: 305–338, 1938.

ture. Ehrenberg [68] has illustrated excellent oriented intergrowths and skeleton crystals of pentlandite in pyrrhotite, no doubt a result of exsolution.

*Silver-Dyscrasite.* Intergrowths involving antimonial silver and dyscrasite have long been known. Some of the intergrowths [69] are suggestive of exsolution and the relations in the constitution diagram silver-antimony are such that there is further reason for believing that the intergrowths are a result of exsolution. Recently Peacock [70] has presented a detailed crystallographic analysis of dyscrasite with additional chemical and microscopic studies. An intergrowth of dyscrasite in predominant antimonial silver from the Kerr Lake mine is a diagrammatic lattice type such as frequently originates by exsolution.

*Sphalerite-Chalcopyrite.* Minute globules and lamellæ of chalcopyrite in sphalerite are probably more commonly observed than any other combination of minerals involved in exsolution. Those referred to here are only the more conspicuous examples. Buerger [71] has conducted careful experiments and furnished valuable conclusions on the problem of the origin of these inclusions. Chalcopyrite seems to mix and unmix in sphalerite at about 400° C. with at least slight solubility ranging down to 350. Shenon [72] believes that chalcopyrite inclusions in sphalerite from the Cowboy mine, Oregon, have formed by unmixing, whereas pyrrhotite inclusions formed by replacement. Eberhard [73] has classified chalcopyrite inclusions in sphalerite as of several types. Edwards notes exsolution inclusions of chalcopyrite in sphalerite where the sphalerite is also cut by veins of chalcopyrite. Good examples of

[68] Ehrenberg, H.: Orientierte verwachsungungen von Magnetkies und Pentlandit. Zeit. Kris., 82: 309–315, 1932.

[69] Schwartz, G. M.: Dyscrasite and the silver-antimony constitution diagram. Am. Min., 13: 495–503, 1928.

[70] Peacock, M. A.: On dyscrasite antimonial silver. Univ. of Toronto. Geol. Ser. No. 44: 31–46, 1940.

[71] Buerger, N. W.: The unmixing of chalcopyrite from sphalerite. Am. Min., 19: 525–530, 1934.

[72] Shenon, P. J.: Chalcopyrite and pyrrhotite inclusions in sphalerite. Am. Min., 17: 514–518, 1932.

[73] Eberhard, C.: Zwei Erzentmischungen von Schneeberg in Tirol. Centr. Min. Abt. A (5): 147–153, 1931.

inclusions of chalcopyrite in sphalerite, which appear to have formed by exsolution, are found in the literature although the author may not mention this fact. Petrulian furnishes a good example.[74]

*Sphalerite-Pyrite.* Ross [75] quotes Short regarding sphalerite from a pegmatite, "In some of the pale colored sphalerite minute uniformly oriented and evenly distributed bleb-like masses of pyrite may be the result of exsolution." The writer has not encountered any other references to this possibility.

*Sphalerite-Pyrrhotite.* Ramdohr [76] includes pyrrhotite among the unmixing products in sphalerite but examples seem rare. Oelsner [77] shows a photograph of the example from Freiberg to which Ramdohr refers. The writer has observed well oriented lamellæ in sphalerite from the Potosi mine, Chihuahua, Mexico.

*Stannite-Chalcopyrite, Stannite-Cubanite, Stannite-Pyrite, Stannite-Sphalerite, Stannite-Tetrahedrite.* Stannite is unusual in the number of minerals which occur as inclusions or oriented intergrowths within it. Several were referred to in the 1931 summary; others have been added. Space will be saved by discussing them under a single heading.

The most common are chalcopyrite and sphalerite. Chalcopyrite has been shown to dissolve in stannite at about 500° C. Ahlfeld [78] has given excellent examples of these intergrowths. Oelsner [79] has described stannite intergrowths in sphalerite, a less common occurrence. Sphalerite with stannite has also been described by Oelsner. Ramdohr [80] includes tetrahedrite and cuba-

[74] Petrulian, N. S.: Etude chalcographique des gisement de plomb et de zinc de Herja. Ann. Inst. Geol. al Romanie, 16: 518, 1934.

[75] Ross, C. S.: Sphalerite from a pegmatite near Spruce Pine, N. C. Am. Min., 22: 643–650, 1937.

[76] Ramdohr, P.: Neue Beobachtungen über die Verwendbarkeit opaker Erze als geologische Thermometer. Zeit. Prakt. Geol., 39: 65–73 and 89–91, 1931.

[77] Oelsner, O.: Beitrage zur Kenntniss der kiesigen Bleierzformation Friebergs. Dissertation, Freiberg, 1929, Fig. 22.

[78] Ahlfeld, F.: Uber Zinnkies. Neues Jahrb. für Mineralogie, Beil., Band 68, Abt. 268–287, 1934.

[79] Oelsner, O., op. cit.

[80] Ramdohr, P., op. cit.

nite in his list of unmixing products in stannite. Cubanite occurs as lamellæ in chalcopyrite inclusions within stannite. The exsolution products in stannite are discussed in some detail by Schneiderhöhn and Ramdohr.

*Stromeyerite-Argentite.* Guild [81] has suggested that certain graphic types of intergrowths of stromeyerite and argentite may be a result of unmixing, but in a later paper replacement is emphasized in graphic textures. Experiments by the writer [82] involving $Cu_2S$ and $Ag_2S$ failed to produce evidence of unmixing of argentite from stromeyerite, although a solubility of as much as 15 per cent $Ag_2S$ in $Cu_2S$ is indicated and of 20 per cent $Cu_2S$ in $Ag_2S$. It must be concluded on the basis of available data that exsolution intergrowths involving stromeyerite and argentite are not known with any certainty.

*Tantalo-Rutile-Ilmenite.* Edwards [83] has described ilmenite bodies oriented in the (111) directions of tantalo-rutile from Melville, West Australia. He says: "The structure indicates that unmixing of a solid solution has led to the development of ilmenite exsolution bodies in the crystallographic directions of the original crystals, and that these exsolution bodies of ilmenite tend to aggregate into coarse crystals."

*Tennantite-Chalcopyrite.* Oelsner [84] illustrates a good example of lamellæ of chalcopyrite oriented along the octahedral planes of tennantite and refers the origin to unmixing. The nature of the texture makes the interpretation a reasonable one.

*Tennantite-Galena.* Oelsner also refers inclusion of galena in tennantite to unmixing. The fact that the galena is concentrated at one end of an irregular inclusion of tennantite in galena leaves considerable doubt about this example in the opinion of the writer. At least the photograph is not convincing.

[81] Guild, F. N.: The enrichment of silver ores. Laboratory Investigation of Ores, chap. XI, McGraw-Hill, 1928.

——: The microtexture and paragenesis of stromeyerite. Schweiz. Min. Petr. Mitt., 12: 222–233, 1932.

[82] Schwartz, G. M.: Chalcocite-stromeyerite-argentite. Econ. Geol., 30: 138–146.

[83] Op. cit.

[84] Op. cit., Fig. 43.

DISCUSSION.

The most striking development of the past ten years in the knowledge of exsolution in ore minerals is the large number of minerals which investigators have assigned to such an origin. This is perhaps an adequate demonstration of the acceptance of the process as important in the formation of ore minerals and textures. The large number of examples assigned to exsolution does not of necessity mean that progress has been satisfactory in other respects. In 1931 tentative criteria were suggested which were thought to indicate that exsolution was the origin of certain intimate intergrowths of minerals. In the numerous papers referred to in the present review there are few attempts to evaluate the criteria which led to the classification of the relationships between minerals as a result of exsolution. Perhaps this implies an acceptance of the 1931 criteria as valid, but they were suggested in the hope of critical evaluation, which would perhaps eliminate some suggestions and add others. Only thus can true progress result.

Progress has been most satisfactory in the examples which have been studied experimentally. These are reviewed above. The complexity of the problems is often very great, however, and this is clearly demonstrated by Merwin and Lombard's paper [85] on the system Cu-Fe-S. In addition to the usual variables of composition and temperature the pressure of sulphur vapor is involved. Literally hundreds of experiments were necessary to outline fields of stability involving only solid phases and vapor.

Some writers refer intergrowths of almost any type to an origin by exsolution, others are more conservative. In reviewing the literature it seemed that German writers are particularly prone to consider inclusions of one mineral in another as a result of unmixing. This may be partly a result of Schneiderhöhn's [86] excellent treatment of the subject at an early date. As examples

[85] Merwin, H. E., and Lombard, R. H.: The system, Cu-Fe-S. ECON. GEOL., 32: 204–242, 1937.

[86] Schneiderhöhn, H.: Entmischungerscheinungen inner halb von Erzmischkristallen, etc. Metall. und Erz, 19: 517–529, 1922.

of questionable unmixing textures one might select Oelsner's [87] figure showing inclusions of galena in tennantite which are confined to one end of the area of tennantite, or of tennantite which forms a sort of matrix to a small piece of galena. The example of very irregularly distributed remnant-like areas of stannite in sphalerite also seems questionable.

It is evident from the review that most investigators consider regular and rather uniformly distributed lamellæ with good crystallographic control by the host mineral as a satisfactory evidence of exsolution.

Some criteria have been cited specifically by various workers and deserve review. Shenon [88] describes inclusions of chalcopyrite and pyrrhotite in sphalerite and concludes that chalcopyrite exsolved whereas pyrrhotite replaced sphalerite. Shenon cites the fact that there is no increase in chalcopyrite inclusions near veins of chalcopyrite in sphalerite nor in sphalerite remnants in chalcopyrite as evidence favoring exsolution. On the other hand laths and blebs of pyrrhotite occur in sphalerite only where pyrrhotite replaces the sphalerite near by. A later sphalerite replaces pyrrhotite yet the younger sphalerite contains as many inclusions of chalcopyrite as does sphalerite replacing chalcopyrite. Criteria such as these seem particularly convincing to the writer.

Stevenson [89] cites the fact that pyrrhotite vermicules in chalcopyrite extinguish as a unit in polarized light and points out that this frequently characterizes the minor constituent in exsolution textures. The fact that these vermicules occur only between crystals of chalcopyrite also is evidence of exsolution. Other criteria fulfilled are: smooth boundaries of pyrrhotite, absence of vermicules outside of chalcopyrite, and narrowing where two or more vermicules form.

Criteria against exsolution are noted by Ödman [90] who found gold abundant as small particles in chalcopyrite but these are irregularly distributed and are varied in form and size.

[87] Op. cit., Figs. 20, 46, 61.
[88] Op. cit.
[89] Op. cit.
[90] Op. cit.

It should be emphasized that greater confidence may be developed in the explanation of a texture as a result of exsolution by experimental work. If polished surfaces of intergrowths are sealed, heated, quenched and then found to have formed a solid solution, the first step, the possibility of a solid solution at elevated temperature, is proven. If the specimen is then reheated and slowly cooled with consequent exsolution the demonstration is complete. This does not prove that every natural texture in which this may be done originates by exsolution but at least it proves the possibility of such origin.

## LIST OF CRITERIA FOR EXSOLUTION.

For convenience the criteria suggested in the 1931 paper are revised and included herewith and additions suggested by the present review are added. Additions and critical evaluations are invited.

1. A crystallographic intergrowth of widely and uniformly distributed minute inclusions. The crystallographic control in the best examples is very definite.

2. Inclusions may be of lamellar, blade, plate, or rod-like forms characterized by sharp smooth boundaries. Minute dendritic, skeletal, or complete crystal forms are known but are less common. If inclusions are no more abundant near veinlets of the same mineral in the host this fact is additional evidence in favor of exsolution.

3. No enlargement where blades of other forms cross or join; often a contraction at intersections.

4. The inclusions are often single crystal units in contrast to veinlets which consist of many units.

5. Lack of relation of included minerals to grain boundaries, cracks, mineral contacts, and other localities where replacement characteristically takes place. Exception is a segregation to grain boundaries; in this case, however, the guest will occur only as inclusions and at grain boundaries.

6. Even distribution of inclusions. Not more abundant at

grain boundaries or along veins. May be less abundant at the outside of grains.

7. Lack of criteria of replacement for regular or oriented mineral intergrowths suggests possibility of exsolution. Any positive criterion of replacement is a negative criterion of exsolution.

8. Absence of the included mineral outside of the intergrowth. If included mineral is also present outside of the intergrowth it becomes indication either for or against exsolution origin, depending on its occurrence. Examples: as veinlets, indicative against exsolution; as contemporaneous grains, indicative of exsolution.

9. Included mineral usually as disconnected units rather than a network as in replacement along cleavage.

10. Orientation of blades differs for each grain of the host mineral, dependent on relation of polished plane to crystal orientation.

11. General similarity of the components in chemical and crystal structure. This indicates *a priori* possibility of the mineral forming a solid solution at higher temperatures.[91] Inversions are, of course, important.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINNESOTA,
*April 20, 1942.*

[91] Gruner, J. W.: Structural reasons for oriented intergrowths in some minerals. Am. Min., 14: 227–239, 1929.
——: Structures of sulfides and sulfosalts. Am. Min., 14: 470–481, 1929.

# POST–MINE LEACHING OF GALENA AND MARMATITE AT BROKEN HILL.

M. D. GARRETTY AND ROLAND BLANCHARD.

ABSTRACT.

At the North mine section of North Broken Hill Limited, in stopes of the 2000- and 2150-ft. levels (1550 ft. and 1700 ft. respectively below base of pre-mine oxidation), and particularly in the portion thereof known as the Northern orebody, galena and marmatite are undergoing rapid post-mine decomposition. Several unique features are associated with the leaching phenomenon. Galena and the lead minerals as a whole are being leached preferentially and with greater rapidity than are marmatite and the zinc minerals as a whole. The galena of the orebody is estimated to be leaching at an average rate of $\pm 0.75$ per cent per year. The phenomenon is not uncommon elsewhere in the Broken Hill district, but has been studied in detail only in the current stoping section of the North mine. Possible causes for preferential leaching of the lead minerals over the zinc minerals are discussed, but a wholly satisfying explanation has not been reached. The more abundant leaching within the Northern orebody is believed to be in part accounted for by a time lag resulting from the level development policy pursued at the North mine. A description is given of leached derivatives of fluorite, which are conspicuously developed at Broken Hill.

CONTENTS.

INTRODUCTION ..... 366
GENERAL GEOLOGICAL SETTING ..... 367
Occurrence of the Leached Products ..... 368
Detailed Nature of the Leached Products ..... 369
Cellular Derivatives of Lead Minerals ..... 369
Cellular Derivatives of Zinc Minerals ..... 370
Cellular Derivatives of Other Sulphides ..... 371
Cellular Derivatives of Fluorite ..... 371
Cellular Derivatives of Calcite ..... 371
Composition of the Leached Cellular Products ..... 372
Redeposition of the Leached Material ..... 373
Recalculated Mineralogical Compositions ..... 380
Redeposition of Lead Minerals ..... 384
Redeposition of Zinc Minerals ..... 386
Redeposition of Metallic Minerals Derived from Other Sulphides ..... 387

SEQUENCE OF LEACHING ..... 388
RATE OF LEACHING ..... 391
SUGGESTED CAUSES FOR THE PREFERENTIAL LEACHING OF GALENA OVER MARMATITE ..... 393
SUGGESTED CAUSES FOR MORE EXTENSIVE LEACHING IN THE NORTHERN OREBODY ..... 402
ACKNOWLEDGMENTS ..... 404
APPENDIX ..... 404
Description of Boxwork Derivatives of Fluorite ..... 404

## INTRODUCTION.

A LIGHT-COLORED, friable, porous material occurs in stopes of the 2000- and 2150-ft. levels in the North mine section of North Broken Hill Limited, especially in stopes that involve the portion known as the Northern orebody. A substantial proportion of the Company's current production is being drawn from this level and the material represents average grade ore from which the lead and zinc minerals and certain gangue constituents have been largely or wholly removed by leaching. The 2000- and 2150-ft. levels lie, respectively, 1550 and 1700 feet below the extreme base of the pre-mine oxidized zone. Composition of the cellular product shows it to be supergene. The oxidation and leaching therefore must be assumed to have taken place since drainage of the affected areas was accomplished by mining operations.

The matter is of more than passing interest, because the post-mine leaching of galena is proceeding here with greater rapidity than is generally ascribed to geologic processes, and because, contrary to standard geologic conception, the lead minerals are being leached more rapidly than are those of zinc.

Similar porous leached material in varying amount has been found in higher, now mostly mined-out, levels within the sulphide zone at the North mine, and has been observed in the deepest (2600-ft. level) workings. In has also been observed within the sulphide zone in the other mines at Broken Hill, though not, to date, in the abundance in which it occurs at the North mine. The connected broad horizontal and vertical range of exposures afforded by stopes of the 2000- and 2150-ft. levels of the North

mine offer exceptional opportunity for observing and mapping the phenomenon in detail, and the scope of the present paper is limited mainly to the leaching phenomenon as expressed at that place.

## GENERAL GEOLOGICAL SETTING.

The North mine contains two major ore lenses known as the Northern and Southern orebodies. They are selective replacements of two horizons of pre-Cambrian strata at a place, within the major Broken Hill lode structure, where the horizons are involved in a group of folds that pitch steeply northward. Although at the North mine the structural behavior of the folds, including their pitch, gives rise to two entirely distinct orebodies in plan, that condition does not obtain for the rest of the district, and the favorable beds elsewhere are known as the No. 2 lens (Northern orebody type) and No. 3 lens (Southern orebody type).

Major sulphides within both lenses are galena and marmatite. For the district the averages in metal content are:

| Lens. | Content Per Ton of Ore. | | |
|---|---|---|---|
| | Ag oz. | % Pb. | % Zn. |
| No. 2..... | 4–5 | 14 | 11 |
| No. 3..... | 8+ | 14 | 16 |

Lesser sulphides commonly associated with the galena and marmatite are pyrite, pyrrhotite, and chalcopyrite, with minor arsenopyrite. The chalcopyrite generally, and the pyrrhotite commonly, occur dispersed through the marmatite as small exsolution blebs.

Sillimanite gneiss constitutes the country rock, and rhodonite, quartz and garnet the principal non-sulphide minerals. In addition to those minerals, which are common to both lenses, fluorite is abundant and widespread in No. 3 lens but sporadic and sparse in No. 2 lens, and calcite is abundant and widespread in No. 2 lens but virtually absent in No. 3 lens.

Other sulphides and other gangue minerals at Broken Hill are subordinate. They are not discussed in this paper.

Several major faults, with horizontal throw up to 2000 feet and vertical displacement up to 2500 feet, cut diagonally across the line of No. 2 and No. 3 lenses, but the portion of the North mine herein discussed is not directly affected by them. Faults of the North mine, of pre-ore origin with slight post-ore movement, though numerous, are of negligible displacement.

*Occurrence of the Leached Products.*

As previously stated, the leaching phenomenon manifests itself chiefly in the Northern orebody, and within that body occurs most of the leaching of galena and marmatite herein described. Leaching in the Southern orebody is less advanced and far less extensive, and is confined more specifically to gangue constituents.

Irrespective of the orebody within which it takes place or the nature of the mineral attacked, the leaching characteristically leaves cavities, a foot or more in size, which occur in belts or chains up to 150 feet long and 1 to 8 feet wide. The larger belts or chains occur exclusively in the Northern orebody.

The belts are elongated with the orebodies in a manner suggesting that certain strata have been preferentially followed. When viewed underground, they suggest concentration of leaching along fault planes, but that is not substantiated by patterns formed by the leached products, or by the presence of readily identified faults beyond the individual patches or areas of leaching. However, at all places where the leached products occur, shattering of the sulphide ore is in evidence to a greater or lesser degree.

A noteworthy feature is the presence of fluorite along the belts of leaching. In the Southern orebody (No. 3 lens), as already noted, fluorite is a characteristic gangue mineral throughout the lens. It occurs in coarsely crystalline masses up to 6 inches across, in finely granular masses up to the same size, and as disseminated grains 1 to 3 mm. across and its association with the galena and marmatite that are undergoing leaching appears to be invariable. On the other hand, in the Northern orebody (No. 2

lens) where the gangue is more calcitic, fluorite is normally completely absent except stratigraphically along the belts of leaching, and although it occurs (sparsely) along those belts, prominent exposures of the mineral in any form are rare. Often its presence is detectable only by microscopic observation or analysis.

Thus, while fluorite appears to be present wherever leaching of galena and marmatite is taking place, and undergoes decomposition with them, the leaching phenomenon bears no proportional relationship to the content of fluorite. Leaching of the galena and marmatite is most abundant, in fact, where fluorite, in the larger sense, is least abundant.

### *Detailed Nature of the Leached Products.*

The leached products occur in all stages of formation. They range from incipient thin webwork "eating its way" as scattered minute gray spots along cleavage or fracture planes in otherwise normal sulphide ore, through the various intermediate stages, to the final thoroughly leached residuals in which there remains only a fragile cellular boxwork or sponge, patterned after grain boundaries of the parent mineral. An opportunity is thus afforded to trace gradationally the complete decomposition processes. It permits establishing, by direct descent, the origin of approximately 95 per cent of the leached material.

The leached products are derived mainly from three sources; galena, marmatite and fluorite. A much smaller percentage is derived from chalcopyrite, pyrite, pyrrhotite, arsenopyrite, and calcite.

*Cellular Derivatives of Lead Minerals.* The cellular leached products of lead origin comprise "cleavage" boxwork and cellular sponge as direct derivatives of galena, and "partially sintered" crusts and diamond-mesh boxwork as derivatives of cerussite. Some of the latter boxwork, which is delicately reticulating meshwork grading into decomposing crystalline cerussite, is exceptionally well developed and preserved.

None of these products is described here in detail; their physical characteristics, and criteria for recognition have been set forth

in previous papers.[1] Examples of direct derivatives of the galena are shown in Figs. 2 and 6; of the cerussite, in Figs. 2, 3 and 4. The cellular sponge of galena origin at Broken Hill tends toward coarser size than that described in the literature (Figs. 3 and 5).

FIG. 1. Typical post-mine leaching product found in the sulphide zone 1500 ft. or more below bottom of pre-mine oxidation at Broken Hill. Specimen represents an original mixture of intergrown galena and marmatite, with included specks of chalcopyrite, pyrrhotite and pyrite. The white highlights represent mostly unleached marmatite residuals. Galena residuals are present as small cubes or grains largely embedded within the porous sponge structure. 2150-ft. level, sill, section 24–25/Q, Northern orebody.

*Cellular Derivatives of Zinc Minerals.* Leached cellular products as direct derivatives of marmatite are chiefly cellular sponge. Direct derivatives of smithsonite are loosely adhering aggregates of limonitic granules, rosettes, and irregular fine angular projections coating walls of the cellular sponge. In some instances the granules compose unit aggregates several centimeters across. These products likewise have been described in previous papers.[1] Examples of direct derivatives of marmatite are shown in Figs. 3, 4 and 5.

[1] Oxidation products derived from sphalerite and galena. ECON. GEOL., Aug., 1927, and Additional limonite types of galena and sphalerite derivation. ECON. GEOL., Nov., 1934.

*Cellular Derivatives of Other Sulphides.* A few fine cellular boxwork types of chalcopyrite derivation [2] have been identified in the leached material. In general, chalcopyrite at Broken Hill is so interspersed through the marmatite that identifying characteristics of its limonitic end products have been masked or obliterated.

For the most part pyrite, pyrrhotite and arsenopyrite are scattered too diffusely through the ore in the leached areas for their limonitic end products to have been preserved as distinct entities, but occasional direct derivatives of the minerals may be detected (Fig. 5).

*Cellular Derivatives of Fluorite.* Leached cellular products of fluorite origin comprise several boxwork types described in the Appendix. The Broken Hill occurrences constitute the first fluorite derivatives clearly recognized as such and studied in the Leached Outcrops investigation. Since their identification at Broken Hill, A. B. Edwards, of the Council for Scientific and Industrial Research (Australia), has noted similar products from Walwa, Victoria. Examples of the leached derivatives are shown in Figs. 9 to 12.

*Cellular Derivatives of Calcite.* Well crystallized calcite of the Northern orebody (No. 2 lens) occasionally yields a limonitic boxwork of distinct rhombohedral pattern. To the experienced observer it is not readily confused with the rhombohedral derivative of cerussite.[3]

[2] Notes on the oxidation products derived from chalcopyrite. ECON. GEOL., Nov., 1925.

[3] The calcite product may be differentiated from the corresponding pseudomorph derived from crystalline cerussite because the calcite product has both longitudinal and cross ribs of more or less uniform thickness. The boxwork consequently is well knit and the pattern generally appears flat and subdued. In the corresponding cerussite derivative the boxwork generally has well defined and commonly paired longitudinal ribs, but imperfect and extremely fragile cross ribs. The structure consequently is less firmly knit, has bolder relief, and the cell walls often are loosely coated with long isolated limonitic projections. In miniature the cerussite derivative resembles the bold open clusters of imperfectly-joined crystals so conspicuous, on a larger scale, in museum specimens of Broken Hill cerussite.

*Composition of the Leached Cellular Products.*

Composition of the leached cellular products ranges from exclusive limonitic jasper, with associated goethite and lepidocrocite (in this paper all forms of hydrated ferric oxide are grouped under the term limonitic jasper), to exclusive supergene carbonate

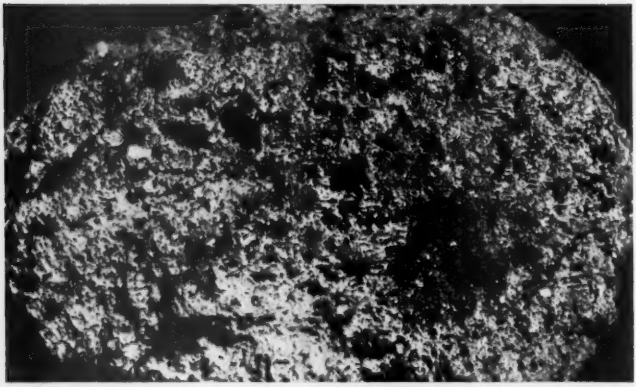

FIG. 2. Specimen 1, Table 1. Original sulphides estimated at 80 per cent galena, 17 per cent marmatite. Parallel walls of "cleavage" boxwork derived from galena, with some cubic box structure, discernible through cerussite and "partially sintered" crusts derived from it. The latter are limonitic jasper and supergene gangue carbonate pseudomorphs after globular cerussite. White highlights represent unleached sulphide residuals, some cubic. Specimen estimated to contain 4.5 per cent galena, 1.5 per cent marmatite, 23.5 per cent cerussite, 11.5 per cent smithsonite; pointing to 68 per cent of total original Pb and 28 per cent of total original Zn having been leached. Much of the smithsonite comprises isolated but numerous fine acicular needles that project as tiny crystals from cell walls. With low residual sulphide content, leaching of total lead and zinc usually is more thorough, as Broken Hill post-mine leached cellular products do not normally retain much lead and zinc as either carbonate or sulphate.

This specimen of cellular material contains appreciably more siliceous component as limonitic jasper than do most Broken Hill cellular leached products (see Table 1). 2000-ft. level, second floor, section 28/P–Q, Northern orebody.

gangue matter. Generally the two products are intergrown, and in some instances irregularly replace each other. The leached products may carry manganese dioxide, small amounts of scorodite, and other impurities.

Dr. Edwards has made careful microscopic and analytical determinations of the boxwork material. He has shown the supergene carbonate gangue matter to be composed of a complex and variable manganese-lime-iron carbonate, with the manganese or lime constituents generally predominating, but with ferrous carbonate always present in substantial amount. Magnesium carbonate may be, but is not always, present.[4]

Although both limonitic jasper and supergene carbonate gangue minerals occur in varying amount in nearly all of the boxwork compositions, limonitic jasper tends to predominate over supergene carbonate gangue matter in leaching of the lead minerals (Table 1). In leaching of the zinc minerals the two products are more nearly in balance (Table 1), but boxworks composed of limonitic jaspar alone have been found as derivatives of essentially pure marmatite.[5]

In leaching of fluorite the supergene carbonate gangue minerals greatly predominate. In leaching of calcite the boxwork is mostly strongly siliceous.

### *Redeposition of Leached Material.*

A noteworthy feature of the boxworks is the generally low content of sulphate and carbonate forms of lead and zinc precipitated within the cellular leached material. The percentage for lead is especially low—far below that found in the oxidized residuals of most lead-zinc districts—despite the presence of

[4] The large amount of supergene carbonate gangue matter in the leached products, and its frequent intimate intergrowth with the limonitic jasper, militates against formation of a rigid and chemically resistant cellular boxwork in the leached products at Broken Hill. The boxwork consequently disintegrates rapidly upon exposure to weathering. That explains why in Broken Hill surface outcrops the preserved gossans are not commensurate with the amount of sulphide known to have been leached at the horizon of the present surface.

[5] Specimen from Northern orebody, 1850-ft. level, north end of main stope.

TABLE 1.

MINERALOGICAL COMPOSITION (PERCENTAGE) OF SIX SELECTED CELLULAR BOXWORKS DERIVED FROM BROKEN HILL (NORTH MINE) HIGH GRADE LEAD-ZINC ORE.

*A. Ore Originally Rich in Galena.*

| | Pb. | Zn. | Cu. | As. | Fe. | Mn. | S. | $SO_3$. | F. | $Al_2O_3$. | $SiO_2$. | CaO. | MgO. | $CO_2$. | Calculated O. | Total. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. 1 | 22.1 | 7.0 | 0.3 | n d | 7.3 | 5.5 | 1.4 | 0.12 | n d | 0.2 | 21.1 | 3.9 | 0.2 | 15.5 | | |
| Galena | 3.9 | | | | | | .6 | | | | | | | | | 4.5 |
| Marmatite | | .87 | | | .13 | .02 | .5 | | | | | | | | | 1.52 |
| Chalcopyrite | | | .3 | | .26 | | .3 | | | | | | | | | .86 |
| Goslarite | | .10 | | | | | | .12 | | | | | | | .21* | .43 |
| Cerussite | 18.2 | | | | | | | | | | | | | 3.86 | 1.40 | 23.46 |
| Smithsonite | | 6.03 | | | | | | | | | | | | 4.06 | 1.48 | 11.57 |
| Supergene carbonate gangue | | | | | 2.67 | 2.74 | | | | | | 3.9 | .2 | 7.58 | 1.56 | 18.65 |
| Limonitic jasper† | | | | | 4.24 | 2.74 | | | | .2 | 21.1 | | | | 3.42 | 31.70 |
| Miscellaneous‡ | | | | | | | | | | | | | | | | 7.31 |
| | 22.1 | 7.00 | .3 | | 7.30 | 5.50 | 1.4 | .12 | | .2 | 21.1 | 3.9 | .2 | 15.50 | 8.07 | 100.00 |
| No. 2 | 2.5 | 2.0 | nil | tr | 8.7 | 8.2 | nil | tr | n d | 0.4 | 49.6 | 4.6 | 1.1 | 13.4 | | |
| Cerussite | 2.5 | | | | | | | | | | | | | .53 | .19 | 3.22 |
| Smithsonite | | 2.0 | | | | | | | | | | | | 1.35 | .49 | 3.84 |
| Supergene carbonate gangue | | | | | 4.34 | 4.1 | | | | | | 4.6 | 1.1 | 11.52 | 2.42 | 28.08 |
| Limonitic jasper† | | | | | 4.36 | 4.1 | | | | .4 | 49.6 | | | | 4.26 | 62.72 |
| Miscellaneous‡ | | | | | | | | | | | | | | | | 2.14 |
| | 2.5 | 2.0 | | | 8.70 | 8.2 | | | | .4 | 49.6 | 4.6 | 1.1 | 13.40 | 7.36 | 100.00 |
| No. 3 | nil | 2.3 | nil | 0.013 | 15.0 | 13.3 | 0.2 | n d | 0.1 | n d | 28.8 | 3.0 | 2.1 | 12.3 | | |
| Marmatite | | .35 | | | .05 | .01 | .2 | | | | | | | | | .61 |
| Smithsonite | | 1.95 | | | | | | | | | | | | 1.31 | .48 | 3.74 |
| Scorodite | | | | .013 | .01 | | | | | | | | | | .017* | .04 |
| Supergene carbonate gangue | | | | | 1.28 | 6.65 | | | | | | 3.0 | 2.1 | 10.99 | 2.31 | 26.33 |
| Hypogene quartz (estimated) | | | | | | | | | | | 5.0± | | | | | 5.00 |
| Limonitic jasper† | | | | | 13.66 | 6.64 | | | | | 23.8 | | | | 9.74 | 53.84 |
| Miscellaneous‡ | | | | | | | | | .1 | | | | | | | 10.44 |
| | | 2.30 | | .013 | 15.00 | 13.30 | .2 | | .1 | | 28.8 | 3.0 | 2.1 | 12.30 | 12.547 | 100.00 |

TABLE 1.—*Continued*

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Limonitic jasper† | | | | | 13.66 | 6.64 | | | | | 23.8 | | | | 9.74 | 33.84 |
| Miscellaneous‡ | | | | | | | | | .1 | | | | | | | 10.44 |
| | | 2.30 | | .013 | 15.00 | 13.30 | .2 | | .1 | | 28.8 | 3.0 | 2.1 | 12.30 | 12.547 | 100.00 |

TABLE 1.—*Continued.*

*B. Ore Originally Rich in Marmatite.*

| | Pb. | Zn. | Cu. | As. | Fe. | Mn. | S. | $SO_3$. | F. | $Al_2O_3$. | $SiO_2$. | CaO. | MgO. | $CO_2$. | Calculated O. | Total. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Superpanner Tails* | | | | | | | | | | | | | | | | |
| No. 4a | 0.1 | 2.0 | 0.2 | 0.02 | 11.6 | 15.7 | 1.4 | 0.06 | 0.2 | n d | 30.2 | 4.2 | 0.2 | 16.0 | | |
| Galena | .1 | | | | | | .02 | | | | | | | | | .12 |
| Marmatite | | 1.95 | | | .3 | .05 | 1.12 | | | | | | | | | 3.42 |
| Chalcopyrite | | | .2 | | .18 | | .2 | | | | | | | | | .58 |
| Pyrrhotite | | | | | .02 | | .01 | | | | | | | | | .03 |
| Pyrite | | | | | .04 | | .05 | | | | | | | | | .09 |
| Goslarite | | .05 | | | | | | .06 | | | | | | | .11* | .22 |
| Scorodite | | | | .02 | .015 | | | | | | | | | | .027* | .062 |
| Supergene carbonate gangue | | | | | 7.9 | 7.83 | | | | | | 4.2 | .2 | 16.0 | 4.52 | 40.65 |
| Hypogene quartz (estimated) | | | | | | | | | | | 6.0± | | | | | 6.00 |
| Limonitic jasper† | | | | | 3.145 | 7.82 | | | | | 24.2 | | | | 5.91 | 41.075 |
| Miscellaneous‡ | | | | | | | | | .2 | | | | | | | 7.753 |
| | .1 | 2.00 | .2 | .02 | 11.600 | 15.70 | 1.40 | .06 | .2 | | 30.2 | 4.2 | .2 | 16.0 | 10.567 | 100.000 |
| No. 5a | 0.3 | 4.0 | 0.5 | 0.02 | 16.2 | 19.8 | 3.3 | 0.13 | 1.0 | n d | 8.9 | 4.4 | 0.7 | 15.4 | | |
| Galena | .3 | | | | | | .05 | | | | | | | | | .35 |
| Marmatite | | 3.5 | | | .53 | .09 | 2.02 | | | | | | | | | 6.14 |
| Chalcopyrite | | | .5 | | .44 | | .5 | | | | | | | | | 1.44 |
| Pyrrhotite | | | | | .26 | | .15 | | | | | | | | | .41 |
| Pyrite | | | | | .51 | | .58 | | | | | | | | | 1.09 |
| Goslarite | | .12 | | | | | | .13 | | | | | | | .24* | .49 |
| Smithsonite | | .38 | | | | | | | | | | | | .25 | .09 | .72 |
| Scorodite | | | | 1.02 | .015 | | | | | | | | | | .027* | .062 |
| Supergene carbonate gangue | | | | | 3.84 | 9.86 | | | | | | 4.4 | .7 | 15.15 | 3.95 | 37.90 |
| Limonitic jasper† | | | | | 10.605 | 9.85 | | | | | 8.9 | | | | 10.30 | 39.655 |
| Miscellaneous‡ | | | | | | | | | 1.0 | | | | | | | 11.743 |
| | .3 | 4.00 | .5 | .02 | 16.200 | 19.80 | 3.30 | .13 | 1.0 | | 8.9 | 4.4 | .7 | 15.40 | 14.607 | 100.000 |

TABLE 1.—*Continued.*

*B. Ore Originally Rich in Marmatite.*

| | Pb. | Zn. | Cu. | As. | Fe. | Mn. | S. | $SO_3$. | F. | $Al_2O_3$. | $SiO_2$. | CaO. | MgO. | $CO_2$. | Calculated O. | Total. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Superpanner Tails* | | | | | | | | | | | | | | | | |
| No. 6a | 0.2 | 4.9 | 0.7 | 0.025 | 14.1 | 18.0 | 4.4 | 0.13 | 0.3 | n d | 17.6 | 2.9 | 2.2 | 15.8 | | |
| Galena | .2 | | | | | | .03 | | | | | | | | | .23 |
| Marmatite | | 4.18 | | | .64 | .11 | 2.41 | | | | | | | | | 7.34 |
| Chalcopyrite | | | .7 | | .61 | | .71 | | | | | | | | | 2.02 |
| Pyrrhotite | | | | | .44 | | .25 | | | | | | | | | .69 |
| Pyrite | | | | | .87 | | 1.00 | | | | | | | | | 1.87 |
| Goslarite | | .12 | | | | | | .13 | | | | | | | .24* | .49 |
| Smithsonite | | .6 | | | | | | | | | | | | .41 | .15 | 1.16 |
| Scorodite | | | | .025 | .02 | | | | | | | | | | .035* | .08 |
| Supergene carbonate gangue | | | | | 4.48 | 8.95 | | | | | | 2.9 | 2.2 | 15.39 | 3.87 | 37.79 |
| Limonitic jasper† | | | | | 7.04 | 8.94 | | | | | 17.6 | | | | 8.24 | 41.82 |
| Miscellaneous‡ | | | | | | | | | .3 | | | | | | | 6.51 |
| | .2 | 4.90 | .7 | .025 | 14.10 | 18.00 | 4.40 | .13 | .3 | | 17.6 | 2.9 | 2.2 | 15.80 | 12.535 | 100.00 |
| *Superpanner Heads* | | | | | | | | | | | | | | | | |
| No. 4b (By weight, 8.2% of 4a and 4b) | 2.8 | 20.2 | 1.2 | 0.075 | 15.4 | 5.3 | 22.2 | 0.13 | 0.1 | n d | 9.0 | 4.2 | 7.2 | 4.4 | | |
| Galena | 2.5 | | | | | | .39 | | | | | | | | | 2.89 |
| Marmatite | | 19.08 | | | 2.90 | .48 | 10.99 | | | | | | | | | 33.45 |
| Chalcopyrite | | | 1.2 | | 1.05 | | 1.21 | | | | | | | | | 3.46 |
| Arsenopyrite | | | | .075 | .056 | | .032 | | | | | | | | | .163 |
| Pyrrhotite | | | | | 3.35 | | 1.92 | | | | | | | | | 5.27 |
| Pyrite | | | | | 6.678 | | 7.658 | | | | | | | | | 14.336 |
| Goslarite | | .12 | | | | | | .13 | | | | | | | .24* | .49 |
| Cerussite | .3 | | | | | | | | | | | | | .06 | .02 | .38 |
| Smithsonite | | 1.0 | | | | | | | | | | | | .68 | .25 | 1.93 |
| Total Metallic Minerals | 2.8 | 20.20 | 1.2 | .075 | 14.034 | .48 | 22.200 | .13 | | | | | | .74 | .51 | 62.369 |

TABLE 1.—*Continued.*

*B. Ore Originally Rich in Marmatite.*

| | Pb. | Zn. | Cu. | As. | Fe. | Mn. | S. | $SO_3$. | F. | $Al_2O_3$. | $SiO_2$. | CaO. | MgO. | $CO_2$. | Calculated O. | Total. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Superpanner Heads* | | | | | | | | | | | | | | | | |
| No. 5b (By weight, 23.6% of 5a and 5b) | 1.85 | 26.3 | 1.6 | 0.013 | 18.8 | 5.1 | 27.9 | 0.15 | 2.2 | n d | 2 0 | 3.3 | 0.3 | 4.4 | | |
| Galena | 1.6 | | | | | | .25 | | | | | | | | | 1.85 |
| Marmatite | | 24.87 | | | 3.78 | .62 | 14.33 | | | | | | | | | 43.60 |
| Chalcopyrite | | | 1.6 | | 1.41 | | 1.61 | | | | | | | | | 4.62 |
| Arsenopyrite | | | | .013 | .010 | | .006 | | | | | | | | | .029 |
| Pyrrhotite | | | | | 4.48 | | 2.57 | | | | | | | | | 7.05 |
| Pyrite | | | | | 7.96 | | 9.134 | | | | | | | | | 17.094 |
| Goslarite | | .13 | | | | | | .15 | | | | | | | .27* | .55 |
| Cerussite | .25 | | | | | | | | | | | | | .05 | .02 | .32 |
| Smithsonite | | 1.3 | | | | | | | | | | | | .88 | .32 | 2.50 |
| Total Metallic Minerals | 1.85 | 26.30 | 1.6 | .013 | 17.64 | .62 | 27.900 | .15 | | | | | | .93 | .61 | 77.613 |
| No. 6b (By weight, 21.7% of 6a and 6b) | 0.6 | 23.6 | 2.7 | 0.025 | 20.5 | 5.3 | 28.9 | 0.2 | 0.4 | n d | 4.4 | 2.0 | 0.4 | 6.6 | | |
| Galena | .6 | | | | | | .09 | | | | | | | | | .69 |
| Marmatite | | 22.24 | | | 3.38 | .56 | 12.81 | | | | | | | | | 38.99 |
| Chalcopyrite | | | 2.7 | | 2.37 | | 2.72 | | | | | | | | | 7.79 |
| Arsenopyrite | | | | .025 | .019 | | .011 | | | | | | | | | .055 |
| Pyrrhotite | | | | | 4.62 | | 2.65 | | | | | | | | | 7.27 |
| Pyrite | | | | | 9.26 | | 10.619 | | | | | | | | | 19.879 |
| Goslarite | | .16 | | | | | | .2 | | | | | | | .35* | .71 |
| Smithsonite | | 1.2 | | | | | | | | | | | | .81 | .30 | 2.31 |
| Total Metallic Minerals | .6 | 23.60 | 2.7 | .025 | 19.649 | .56 | 28.900 | .2 | | | | | | .81 | .65 | 77.694 |

TABLE 1.—*Continued.*

*B. Ore Originally Rich in Marmatite.*

| | Pb. | Zn. | Cu. | As. | Fe. | Mn. | S. | $SO_3$. | F. | $Al_2O_3$. | $SiO_2$. | CaO. | MgO. | $CO_2$. | Calculated O. | Total. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Composite Analyses (Calculated)* | | | | | | | | | | | | | | | | |
| Nos. 4a and 4b | 0.32 | 3.49 | 0.28 | 0.025 | 11.92 | 14.85 | 3.11 | 0.066 | 0.19 | n d | 28.46 | 4.20 | 0.77 | 15.05 | | |
| Nos. 5a and 5b | 0.67 | 9.26 | 0.76 | 0.084 | 16.81 | 16.33 | 9.11 | 0.135 | 1.28 | n d | 7.27 | 4.14 | 0.61 | 12.80 | | |
| Nos. 6a and 6b | 0.29 | 8.96 | 1.13 | 0.025 | 15.49 | 15.24 | 9.72 | 0.145 | 0.32 | n d | 14.74 | 2.70 | 1.82 | 13.80 | | |

*Content of Sulphides and Their Oxidized Equivalents Remaining Within the Cellular Boxworks.§*

| | No. 1. | No. 2. | No. 3. | Nos. 4a and 4b. | Nos. 5a and 5b. | Nos. 6a and 6b. |
|---|---|---|---|---|---|---|
| Galena | 4.50 | | | .35 | .70 | .33 |
| Marmatite | 1.52 | | .61 | 5.88 | 14.98 | 14.21 |
| Chalcopyrite | .86 | | | .82 | 2.19 | 3.27 |
| Arsenopyrite | | | | .03 | .01 | .01 |
| Pyrrhotite | | | | .46 | 1.98 | 2.12 |
| Pyrite | | | | 1.26 | 4.87 | 5.78 |
| Goslarite | .43 | | | .24 | .51 | .54 |
| Cerussite | 23.46 | 3.22 | | .03 | .08 | |
| Smithsonite | 11.57 | 3.84 | 3.74 | .16 | 1.14 | 1.41 |
| Scorodite | | | .04 | .06 | .05 | .06 |
| | 42.34 | 7.06 | 4.39 | 9.29 | 26.51 | 27.73 |

* Includes water of crystallization.
† Excludes adsorbed and capillary water and water of crystallization.
‡ Largely adsorbed and capillary water, and water of crystallization of the "limonite."
§ Excludes hydrated ferric oxides except those present in scorodite.

abundant lime-neutralizer, particularly in gangue of the Northern orebody, where the leaching is most abundantly developed.

As a check against the impressions gained from underground observations, twenty-six hand specimens embracing all phases of galena-marmatite leaching were selected for detailed microscopic study. The specimens were representative in every respect of the

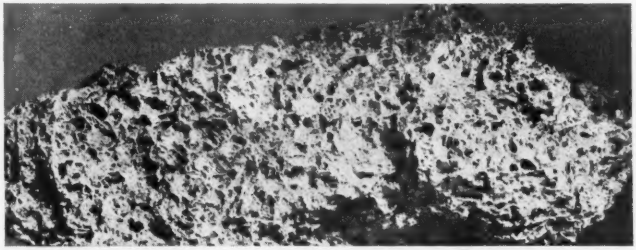

FIG. 3. Specimen 2, Table 1. Original sulphides estimated at 55 per cent galena, 40 per cent marmatite. Typical sponge structure, formed by limonitic webwork during oxidation penetrating along coarse sulphide grain boundaries. Many of the larger cells contain within them the thin parallel cellular walls of "cleavage" boxwork, and several contain pseudomorphs after cerussite. Much of the remaining spongework is of lead origin (poorly disclosed). Field experience indicates that sponge structure is more likely to be of zinc sulphide than of lead sulphide origin. No sulphide residuals present. 95 per cent of total original Pb and 91 per cent of total original Zn are estimated to have been leached. Unleached metallic components comprise 3.2 per cent cerussite and 3.8 per cent smithsonite. In this specimen the siliceous component of the cellular material is even higher than in Fig. 2 (see Table 1). 2150-ft. level, sill, section 25/Q, Northern orebody.

sulphide ore along the belts of leaching, and included material which represented low, average, and high grade ore. Of the total number of specimens, six were selected for analysis as a check against the microscopic observations.

In order that the analyses might disclose optimum conditions over the full range of galena-marmatite variations, the six specimens were chosen to represent, as nearly as possible: (1) galena-

rich-marmatite-poor, and marmatite-rich-galena-poor sequences of leaching; (2) material in which leaching of the lead and zinc minerals was in some instances only moderately advanced and in other instances essentially complete; and (3) material comprising limonitic jasper compositions in which, for individual specimens, the $SiO_2$ content ranged from sparse to abundant. The specimens for analysis likewise were purposely chosen from the massive, high grade, sulphide type of ore in order that indigenous extraneous influences affecting the leaching would be at a minimum. With these qualifications, the six specimens were typical in all respects of the twenty-six, and of the ore of the North mine as a whole.

Because the marmatite-rich-galena-poor suite by chance contained greater residual sulphide than did the galena-rich-marmatite-poor suite, its three specimens were crushed to 35-mesh, and treated in the superpanner.[6] A clean tail was not obtained, as fine sulphide invariably passed over with the coarser gangue in all sizings. Substantial separation of sulphides and gangue nevertheless was effected. Heads and tails were analysed separately.

### *Recalculated Mineralogical Compositions.*

Analyses of material derived from the six specimens, together with recalculated mineralogical compositions based both upon analyses and microscope inspection of the powdered material, are presented in Table 1.

Broken Hill marmatite carries a substantial amount of isomorphous iron. Dr. Stillwell has shown that a small percentage of manganese, which usually, though not always, accompanies the

[6] Average sizings were:

| Mesh (Tyler). | Percentage. | Cumulative Percentage. |
|---|---|---|
| Plus 48 | 27.2 | 27.2 |
| " 65 | 15.0 | 42.2 |
| " 100 | 12.9 | 55.1 |
| " 150 | 12.1 | 67.2 |
| " 200 | 9.4 | 76.6 |
| Minus 200 | 23.4 | |

Each fraction was panned separately.

FIG. 4. Specimens 4a and 4b, Table 1, prior to superpanner treatment. Original sulphides estimated at 28 per cent galena, 58 per cent marmatite. Mostly cellular sponge of zinc sulphide derivation, characterised by its crinkly cell wall structure and dry, empty appearance of the cells. In upper left center are pseudomorphs after crystalline cerussite, and scattered remnants of "cleavage" boxwork. Top of specimen, particularly at center and right, carries "partially sintered" crusts of globular cerussite origin, and consisted originally of a nodule of galena, which passed through the globular cerussite stage before final leaching of its lead constituents. Leached derivatives of both chalcopyrite and pyrite are present. 98.7 per cent of total original Pb and 89.5 per cent of total original Zn have been leached; but specimen still contains 0.35 per cent galena, 5.9 per cent marmatite, 0.8 per cent chalcopyrite, and 1.7 per cent pyrite and pyrrhotite, as sulphide residuals. Oxidized lead and zinc minerals together constitute only 0.43 per cent (see Table 1). The disproportionately high residual sulphide content and low metallic carbonate and sulphate content are characteristic of most Broken Hill boxworks whose sulphide leaching is incomplete. Fig. 2 is an exception in that respect; it was included in the group of analyses partly because of that fact. 2000-ft. level, sill, section 28/P–Q, Northern orebody.

marmatite, is likewise probably isomorphous with the zinc.[7] In the present paper the isomorphous iron and manganese are calculated in accordance with analyses of zinc concentrates by Broken Hill South Limited, arranged over the period 1937–40, as the amount of material thus represented greatly exceeds that available in analyses from other sources. After allowing for known foreign substances, the average analysis by Broken Hill South Limited yields:

| % Zn. | % Fe. | % Mn. |
|---|---|---|
| 56.2 | 8.67 | 1.40 |

In the six specimens analyzed it was noted that, on the average, they contained from one-fourth to one-third as much pyrrhotite as pyrite. Therefore, in the calculations of Table 1, sulphur remaining after satisfying other sulphide requirements is distributed on that basis. $SO_3$ is assigned to goslarite, as no other sulphate was detected under the microscope.

The respective amounts of manganese present, on the average, as supergene carbonate gangue and as an $MnO_2$ constituent of the limonitic jasper, are not readily determined. Since manganese exists in both products in substantial amount, it has been divided equally between them in the calculations, but possibly predominates slightly in the supergene carbonate product.

The microscope disclosed residuals of garnet, apatite, and other related primary gangue minerals which had resisted decomposition. In none of the six specimens (as distinguished from the superpanner heads), did such minerals constitute as much as 2 per cent of the total. In Specimen No. 2, no primary minerals were observed.

Neither was fluorite identified under the microscope in any of the six analysed specimens, though it was observed in seven of the original twenty-six. Fluorine of the analyses in Table 1 is assumed to occur in an unrecognized supergene form.

Mineralogical calculations of Table 1, carried out on the above

[7] The composition of zincblende and the occurrence of gold in the Broken Hill Lode. Mineragraphic Invest. for the Council for Sci. and Ind. Research, Rept. 148, March, 1939.

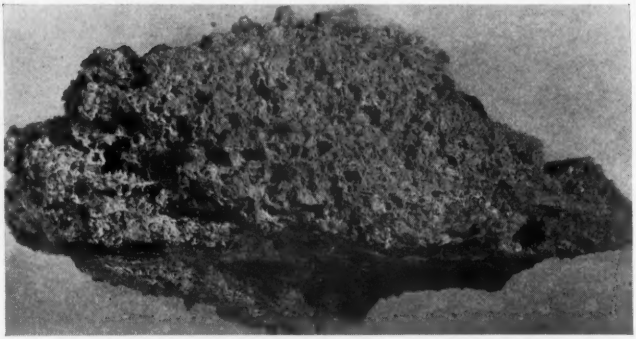

FIG. 5. Specimens 5a and 5b, Table 1, prior to superpanner treatment. Original sulphides estimated at 17 per cent galena, 70 per cent marmatite. Portion considered is that above supergene gangue carbonate layer (partly shaded) near the base. Specimen represents example of cellular sponge, additional to that of Fig. 4, derived largely from marmatite, but originally carrying appreciable galena and important amounts of chalcopyrite, pyrrhotite and pyrite. Most cells are of the crinkly, zinc sulphide type; but there are scattered ghosts of "cleavage" boxwork, and "partially sintered" crusts of globular cerussite coat numerous cell walls. No concentration of galena as a large nodule as in Fig. 4. Near left end of specimen occur three prominent cubic casts after pyrite. Specimen photographed to expose most strongly leached portion; reverse side and interior contained substantial amounts of residual sulphides.

Microscope examination and analysis point to 95.4 per cent of total original Pb and 76.8 per cent of total original Zn having been leached, with 0.70 per cent galena, 14.98 per cent marmatite, 2.2 per cent chalcopyrite, and 6.85 per cent pyrite-pyrrhotite remaining, and with total of only 1.73 per cent oxidized lead and zinc minerals remaining in the cellular mass. Strong leaching of galena and marmatite preferentially to pyrite, and especially to chalcopyrite, is characteristic of Broken Hill sulphides. As in Fig. 4, limonitic jasper and supergene gangue carbonate of the boxwork are in more even balance (see Table 1) than in Figs. 2 and 3. This type of boxwork, with high percentage of supergene carbonate gangue content, crumbles and erodes rapidly upon exposure to weathering, and explains in large part why gossans over Broken Hill orebodies are on the whole incommensurate with total sulphides known to have been leached from the horizon of the present surface. 2000-ft. level, sill, section 28/P–Q, Northern orebody.

described bases, probably involve minor errors as to pyrite, pyrrhotite, supergene carbonate gangue and limonite jasper content, but a check by microscopic observation shows the errors cannot be appreciable ones.

*Redeposition of Lead Minerals.* The redeposited lead minerals comprise crystalline and globular cerussite, anglesite, and secondary galena.

Crystalline cerussite is found sparingly, in the transitional phase, decomposing to limonitic diamond-mesh boxwork. Globular cerussite is more abundant. Occasionally it comprises up to 25 per cent of a hand specimen of the cellular gossan, as in Fig. 2, whose content of "partially sintered" limonitic crusts testifies to several times that amount of globular cerussite having been leached from the specimen. In general, cerussite in any form is rare within the leached material, as indicated macroscopically underground, and microscopically in the twenty-six specimens examined.

Anglesite occurs even more sparingly. It has been observed only in minute amount underground, and none was found in the twenty-six specimens examined under the microscope. Furthermore, although leaching of galena takes place extensively in the North mine, and although the mine water is moderately high in $SO_3$ content, lead sulphate has not been detected as a precipitate in the mine drainage circuit. In fact one of the features which never fails to arrest the attention of the observer is the complete lack of oxidation tarnish upon a large proportion of the galena and marmatite residuals which stud the porous cellular masses.

Crystals of secondary galena are common at Broken Hill. They occur as octahedrons up to 4 mm. across, averaging 1 to 2 mm. Usually they coat walls of fault breccia zones or of the shattered ground generally. Though faults of the North mine, as previously noted, are pre-ore in origin, they usually show post-ore movement, and galena crystals which coat faces of fragments of ore in the breccia of that type are of undoubted supergene origin. On the other hand, only those crystals which are present within and coat the strongly leached boxwork may be regarded

with assurance as of post-leaching origin. Examples of the latter are not uncommon, but they constitute only a small percentage of the total. Whether all of the secondary galena crystals have been similarly deposited in recent post-leaching time is not determinable from existing data, but even if they have been so deposited, they too, in turn, would account for only a very small percentage of the total lead leached from the boxworks.

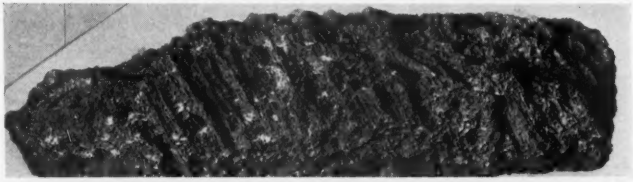

FIG. 6. Leached outcrop from surface over Junction orebody, Broken Hill, derived from massive galena. Note well preserved long parallel cell walls of "cleavage" boxwork, with cross structures producing cubic boxes. Such preservation, in an outcrop long exposed to weathering, means that the boxwork is dominantly siliceous. In general, Broken Hill cellular derivatives of galena are more siliceous (*i.e.*, contain greater limonitic jasper content) than are derivatives of marmatite, both at the surface and in deep post-mine leaching; but highly siliceous cellular sponge of essentially pure marmatite derivation has been found. In Fig. 6 the siliceous boxwork in part has been coated over by deposition of supergene gangue carbonate, and the whole stained by hydrous manganese dioxide; but the original galena pattern has been preserved and stands out prominently from beneath the carbonate and manganese coatings.

Thus, although cerussite, anglesite, and supergene galena are present within the leached material, their combined content falls far short of accounting for the total sulphide lead which has gone into solution.

As a check against the underground and microscopic observations, the following procedure was carried out. For the days August 12 and 13, 1940, when no contribution to the mill was being made by the partly oxidized ore from the British mine, the Northern orebody of the North mine contributed 419 tons, or 13.1 per cent of the total production. So far as observation

could determine, average ore was being stoped. A representative sample of the ore from the roll feed belt taken at the appropriate time (August 15, 1940), gave a fraction, finer than 100-mesh, that comprised between 2 and 3 per cent of the whole. It contained 0.95 per cent oxidized Pb. The bulk ore therefore contained at least 0.019 to 0.028 per cent oxidized Pb. Stated in terms of metal, and taking 15 per cent Pb as the mill head grade for the period in question, oxidized lead should have constituted 0.127 to 0.187 per cent of the total lead. The amount of such oxidized lead in the fines of the mill feed would be a minimum for the ore as a whole, because some of the oxidized lead presumably would be coarser than 100-mesh.

Because of marked variation in occurrence from place to place, and because of usually low content at any place, the *average* percentage of oxidized lead minerals contained within the leached boxwork is difficult to estimate macroscopically or microscopically. The highest estimate arrived at thus far is several times lower than 0.127 per cent of the total lead involved in the orebody. Since the mine water analysis [8] and the mine drainage circuit point to little or no lead being exported from limits of the orebody, it must be assumed that most of the lead removed from the sulphide in leaching remains, if not within the leached product, at least not far removed from it, possibly in the interstices of unaltered sulphide ore as intergranular coatings.[9]

*Redeposition of Zinc Minerals.* The redeposited zinc minerals comprise smithsonite and goslarite.

[8] Analysis of water believed to be free from contamination by mine drainage (taken from a selected diamond drillhole, No. 221, 2450-ft. level, 7/6/40) yielded:

Total solids in solution—878 grains per gallon

| | | | | |
|---|---|---|---|---|
| Pb | —nil | " | " | " |
| Zn | — 28 | " | " | " |
| Mn | — 20.6 | " | " | " |
| Fe | — nil | " | " | " |
| Cl | —164 | " | " | " |
| F | — nil | " | " | " |
| $SO_3$ | —400 | " | " | " |
| $CO_2$ | — nil | " | " | " |

pH value: 6.4

[9] Although only cerussite, anglesite, and secondary galena have been recognized as redepositions of the leached lead, it is possible that, in minor amount, more rare forms of supergene lead products may be present.

Smithsonite, as minute colorless needles up to 1.5 mm. long and superficially resembling tiny quartz crystals, often encrusts the porous cellular masses in varying degree, but is not always present even though marmatite residuals remain.[10] Occasional small masses, up to an inch or more across, of granular smithsonite have been observed. Goslarite usually is discernible in minute amount under the microscope wherever marmatite leaching is incomplete, but no calamine (zinc silicate) has been observed in the material investigated. Neither has supergene zinc sulphide been recognized as such in the deposit.

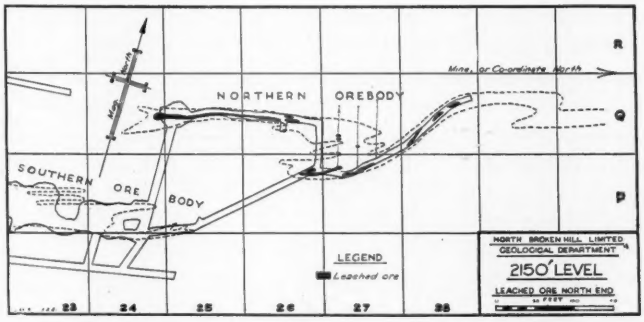


Figure 7

Analysis of the sample from the roll feed belt taken August 15, 1940, yielded 0.4 per cent oxidized Zn, against 0.95 per cent oxidized Pb. Since the Northern orebody contains approximately equal proportions of galena and marmatite it would appear that, except insofar as unrecognized supergene zinc sulphide may be present, a substantial proportion of the dissolved zinc has been exported from limits of the Northern orebody.

*Redeposition of Metallic Minerals Derived from Other Sulphides.* Copper carbonate, resulting from decomposition of small grains of chalcopyrite (with minor tetrahedrite) scattered through

[10] It is the more or less pseudomorphic replacement of these needles which gives rise to the irregular small angular limonitic projections that coat and emerge from walls of the cellular sponge left by leaching of marmatite.

the sulphide ore, has been observed as stains upon the cellular boxwork, but is rare.

Scorodite, presumably as an alteration product from arsenopyrite (with minor löllingite), has been detected sparingly under the microscope.

## SEQUENCE OF LEACHING.

Extended underground observations show that fluorite is the first mineral to undergo leaching. Once started, its leaching proceeds rapidly, and it is not unusual to find the mineral completely decomposed before the surrounding sulphides have been noticeably affected. The condition shown in Fig. 11 is typical.

Next in order of leaching, among the major constituents, are galena and marmatite.

A unique feature is that oxidation of galena precedes that of marmatite. In fact, leaching of the lead minerals as a whole proceeds more rapidly than does that of the zinc minerals as a whole. This is obvious throughout the leached areas where the sulphide residuals which remain to stud the porous mass, as in Fig. 1, usually consist overwhelmingly of marmatite. Exceptions occur, but the condition throughout all types of sulphide mixtures found underground is too general for it to be argued that such occurrences represent only bands or areas of marmatite-rich-galena-poor ore.

In this connection results of the six analyzed specimens are of interest. Prior to crushing for analysis, careful estimate was made of the galena and marmatite originally present. The estimates were based upon evidence yielded by the boxworks and other limonitic replicas, as defined in the earlier portion of this paper. In such "leached outcrop" estimates, where the replica involved has been derived from massive sulphide, an error of 5 per cent for the higher grade ore, and 2 to 3 per cent for the medium grade ore, is conceded, but such error would not affect the picture materially. In order that a permanent record might be preserved of the types of limonitic products yielded by the analyzed specimens—to serve as a check against estimates of the

original galena and marmatite contents—four of the more representative of the six specimens were photographed before crushing. The photographs are reproduced in Figs. 2, 3, 4 and 5.

Results of the estimates, together with the evidence from analyses, are presented in Table 2. The results corroborate the conditions noted macroscopically underground, and leave no doubt

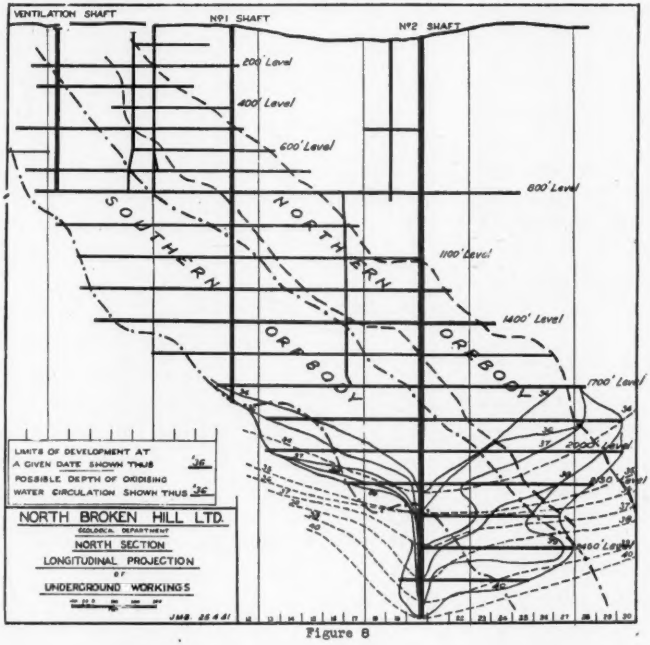


Figure 8

that, in the phenomenon that is taking place along the belts of leaching in stopes of the 2000- and 2150-ft. levels in the Northern orebody of the North mine at Broken Hill, leaching of galena and of the lead minerals as a whole proceeds preferentially and more rapidly than does leaching of marmatite and of the zinc minerals as a whole.

TABLE 2.

TABLE SHOWING EXTENT OF ESTIMATED GALENA, MARMATITE, AND TOTAL LEAD AND ZINC LEACHING WITHIN BROKEN HILL CELLULAR BOXWORKS.

(*Expressed in Per Cent.*)

| Specimen. | Estimated Original Galena Content. | Theoretical Pb Content. | Estimated Original Marmatite Content. | Theoretical Zn Content. | Galena Remaining. | Oxidized Pb Minerals Remaining. | Marmatite Remaining. | Oxidized Zn Minerals Remaining. | Total Sulphide Minerals Remaining. | Total Sulphide Minerals and/or Their Oxidized Equivalents Remaining.* | Galena Leached. | Total Pb Leached. | Marmatite Leached. | Total Zn Leached. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 80 | 69.3 | 17 | 9.7 | 4.5 | 23.46 | 1.52 | 12.00 | 6.88 | 42.34 | 94.4 | 68.1 | 91.1 | 27.8 |
| 2 | 55 | 47.6 | 40 | 22.8 | nil | 3.22 | nil | 3.84 | nil | 7.06 | 100.0 | 94.7 | 100.0 | 91.2 |
| 3 | 40 | 34.6 | 45 | 25.6 | nil | nil | .61 | 3.74 | .61 | 4.39 | 100.0 | 100.0 | 98.6 | 91.1 |
| 4a and 4b | 28 | 24.3 | 58 | 33.1 | .35 | .03 | 5.88 | .40 | 8.80 | 9.29 | 98.8 | 98.7 | 89.9 | 89.5 |
| 5a and 5b | 17 | 14.7 | 70 | 39.9 | .70 | .08 | 14.98 | 1.65 | 24.73 | 26.51 | 95.9 | 95.4 | 78.6 | 76.8 |
| 6a and 6b | 10 | 8.7 | 75 | 42.7 | .33 | nil | 14.21 | 1.95 | 25.72 | 27.73 | 96.7 | 96.7 | 81.1 | 79.0 |
| | | | | | | | | | | | 97.63 | 92.27 | 89.88 | 75.90 |

* Excludes hydrated ferric oxides except those present in scorodite.

Another feature disclosed by the analyses of Table 1 (corroborating microscope observation) is that both galena and marmatite undergo nearly complete leaching while most of the chalcopyrite, and a disporportionately large amount of pyrite, remain unoxidized.

Summarizing, the indicated sequence of decomposition and leaching for the more important minerals is fluorite, galena, marmatite, pyrrhotite, pyrite, chalcopyrite. The position of arsenopyrite is not established, but its decomposition precedes that of chalcopyrite and of much of the pyrite.

## RATE OF LEACHING.

Detailed underground geologic mapping at North Broken Hill Limited has been conducted only during the past few years. Concrete data as to extent of leaching therefore are available on a comprehensive scale only for ground between the 1850- and the 2150-ft. levels. Fig. 7 shows the extent of such leaching within the Northern orebody for the 2150-ft. level. Leaching is not confined to the widths shown, but to facilitate tonnage estimates the zones (consisting of poorly, well, and wholly leached ore) have been reduced to an estimated equivalent width of wholly leached ore. Assuming density corresponding to 10 cu. ft. per ton, the tonnages of original ore (now removed) were:

| | | | | | |
|---|---|---|---|---|---|
| 1850-ft. stope | 46.1 | tons | per | vertical | ft. |
| 2000-ft. level | 29.1 | " | " | " | " |
| 2150-ft. level | 85.6 | " | " | " | " |
| Average | 53.6 | " | " | " | " |

For the ground in question, the Northern orebody yields an average of 2000 tons per vertical foot. Accepting the three areas as a representative average, 2.7 per cent of the ore therefore has been leached of its lead and zinc minerals.

This would indicate that 0.354 per cent of the total lead content (2.7 per cent of 13.1 per cent [11]) had been leached. The figure

[11] 13.1 per cent being the proportion of the total mill feed contributed at the time by the Northern orebody.

compares with the 0.127 to 0.187 per cent in the sample taken from the roll feed belt on August 15, 1940.

The figure 0.354 per cent may be on the high side because, in the underground mapping, microscopic investigation is not feasi-

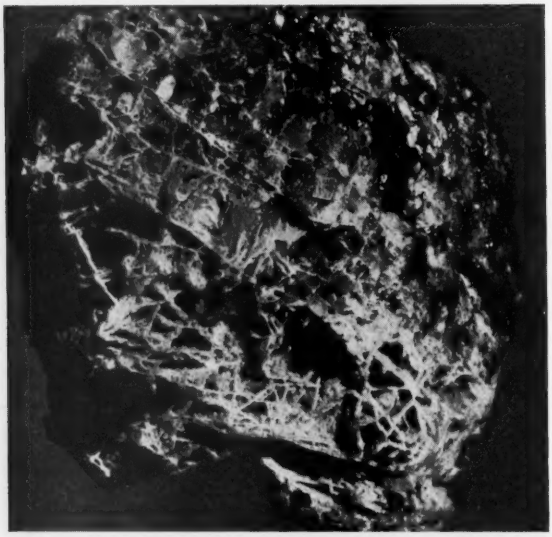

FIG. 9. Cellular boxwork forming from decomposition of massive crystalline fluorite. Fluorite appears to be the first hypogene mineral to undergo decomposition when the sulphide zone at Broken Hill is dewatered. The boxwork forms through minutely thin webs of limonitic jasper or supergene gangue carbonate minerals penetrating along cleavage planes, as in central portion of this specimen. As decomposition proceeds, the webwork thickens—usually by stubby crystals or granules of supergene gangue carbonate encrusting themselves upon the webwork or cell walls. 2000-ft. level, 8th floor, section 18 stope, Southern orebody. × 1.6.

ble, and small amounts of sulphide may exist in material which macroscopically appears to be completely leached. On the other hand, the figures based upon the sample from the roll feed belt probably are on the low side.

The discrepancy, in any event, is in the right direction, and is regarded as reasonable in view of the variations in leaching at the different levels noted above.

To estimate the time during which post-mine leaching can have been operating, the longitudinal projection of Fig. 8 has been prepared. It shows relation of development to water level during the last 5 years.[12] The solid lines represent boundaries of the development in depth at the end of each calendar year, and the broken lines, the lowest level at which active ground water flow would be effective at the appropriate dates. The latter lines do not indicate the water table, or top of the zone of saturation, but merely the depth to which flow of oxidizing surface waters could be brought by means of the circulation set up. The precise positions are speculative, but are limited in depth by the horizontal plane through sump of the shaft, and in height by extreme ends of development openings. Main circulation would take place along fault or shatter zones, and water in the more solid ore or rock might well be more or less stagnant and reducing in nature.

From the curves it may be seen that the north end of the 2000-ft. level has been exposed to the oxidizing circulation for approximately 3 years, and the north end of the 2150-ft. level from 3 to 4 years, before mining.[13]

Extent of leaching for the three areas shows inconsistency, but assuming that the areas constitute a representative average, indicated rate of leaching of the galena would be, as a round figure, 0.75 per cent per year of post-mine exposure.

## SUGGESTED CAUSES FOR THE PREFERENTIAL LEACHING OF GALENA OVER MARMATITE

That Broken Hill marmatite should leach rapidly is expected; rapid decomposition of zinc sulphide is a well known feature in most lead-zinc districts.

[12] The section was constructed in February, 1941.

[13] The figures represent minimum periods as diamond drillholes, put in prior to the development headings, presumably would have started the drainage circulation before the headings penetrated the orebodies.

The special conditions, however, which cause the galena at Broken Hill to decompose more rapidly than the marmatite, have not been fully determined.

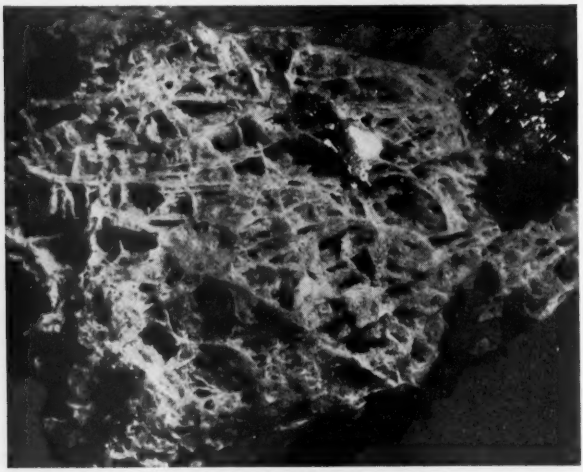

FIG. 10. More advanced stage in decomposition of massive crystalline fluorite. Although limonitic jasper is a constituent of the boxwork, the cellular derivative of fluorite in all Broken Hill specimens examined consists preponderantly of supergene gangue carbonates. Coating of cell walls by fine stubby supergene gangue carbonate crystals and granules has occurred extensively in upper central portion of specimen. Under higher magnification (× 10 upwards) many of the stubby crystals disclose the stacked-cordwood pattern. Upper left portion of specimen consists of a galena nodule (note prominent cubic cleavage cracks). Although most of the fluorite has been leached, the galena has undergone almost no alteration, even along the fluorite contacts. 2000-ft. level, 3rd floor, section 23/O, Southern orebody (overwall). × 1.6.

Factors affecting such leaching, which merit consideration, are:

1. Although the belts of leaching cannot be correlated with known faults, it is undeniable that shattering in varying degree is in evidence wherever leaching is taking place. Such shattering facilitates circulation of ground water which, within the channels

of circulation, may be presumed to carry dissolved oxygen. On the other hand, similar lenses of shattering within the ore elsewhere, and so far as known subjected to the same rate of water circulation, have not undergone leaching. The shattering and ground water circulation by themselves therefore cannot be the sole determinants, though they may be important contributory factors, as discussed under "Suggested Causes for More Extensive Leaching in the Northern Orebody."

2. A casual relationship between fluorite and rapid leaching of the galena and marmatite is suggested by: practical restriction of leaching to the vicinity of nodular fluorite in the Southern orebody; the common finding of small amounts of fluorite in association with the leached zones in the Northern orebody, despite its general absence as a gangue constituent at that place; and the established preferential leaching of fluorite ahead of the sulphides. If, however, the association of decomposing fluorite were a major or important factor in decomposition of the sulphides, leaching of galena and marmatite ought to be much more pronounced and widespread in the Southern orebody (No. 3 lens), where fluorite is general, and is a characteristic gangue mineral. Leaching of galena and marmatite is far more extensive, however, within the Northern orebody.

Similarly, if prior leaching of fluorite facilitates circulation of ground water and oxygen within the affected strata, as presumably it must, by the same token the leaching phenomenon ought to assert itself most strongly in the Southern orebody and not in the Northern.

Tunell [14] has pointed out that before a guess may be hazarded as to the role played by fluorine in the solution of lead and zinc minerals it would be necessary to have specific data regarding concentration of sulphuric acid in the leaching solutions, and probably other precise information, not now available. At present the role played by fluorine in the leaching cannot be appraised, but existing information does not point to it being an important

[14] George Tunell, Geophysical Laboratory, Washington, D. C. Personal communication.

factor, except insofar as its prior leaching facilitates circulation of ground water and oxygen. Even so the sulphide leaching is in no sense proportional to the porosity induced by leaching of the fluorite.

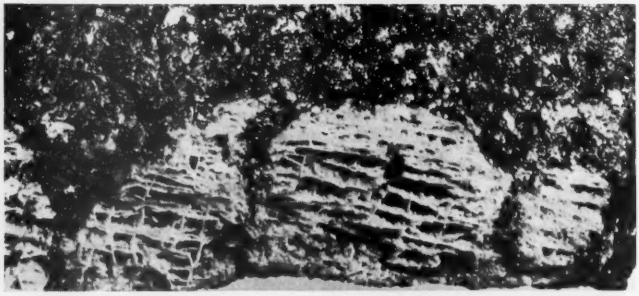

FIG. 11. Nodules of crystalline fluorite completely leached within a massive, coarsely granular, galena-marmatite mixture which barely shows oxidation. Such cellular boxwork may appear to be a derivative of the sulphides. At no place, however, does the boxwork pass by gradation into the sulphides, and it possesses distinguishing characteristics which serve as criteria for its identification. Pseudoparallelism of its longitudinal ribs, and frequent cross webs, impart a superficial resemblance to "cleavage" boxwork of galena derivation. The longitudinal ribs however are not rigidly parallel, and the obtuse angle with them, formed by the cross structures, presumably is a reflection of fluorite's strong octahedral cleavage.

*Note:* White highlights, unlike those of Figs. 3 and 4, are not alone sulphide residuals in an otherwise leached porous mass, as virtually none of the specimen except the fluorite nodules has undergone decomposition or leaching. They represent sulphide cleavages which strongly reflected the light during photographic exposure. Cubic outlines of some of the highlight reflections identify the mineral in the photograph as galena; most of the reflections are from marmatite. Visually estimated composition of the sulphide mass is 52 per cent to 54 per cent marmatite, 45 per cent to 48 per cent galena, 1 ± per cent of chalcopyrite. 2000-ft. level, 12th floor, section 18 stope, Southern orebody.

3. Elongation of the belts of leaching in a manner to suggest that specific strata are involved affords intriguing speculative

possibilities, wholly aside from the presence of fluorite. It suggests that certain associated minerals other than fluorite may be instrumental in effecting the rapid decomposition of sulphides. Thus far, however, search for such possibly "catalytic" associates, within the belts of leaching, has disclosed no minerals that are not equally present within the unleached portions.

4. Absence, or restricted formation, of anglesite in the leached material facilitates rapid decomposition of the galena because it eliminates, or greatly reduces, formation of the inhibiting sulphate coating that so commonly surrounds galena cores in districts where galena persists to the surface through the oxidized zone. Reasons for the very restricted formation of anglesite are less obvious.

5. Although cerussite exists in the leached material, the amount is hopelessly inadequate to account for the amount of galena that has been leached. In much of the cellular material it is entirely absent, even though untarnished galena residuals, which stud the porous mass, may constitute from 10 to 20 per cent of the whole.

An estimate, based upon examination of the twenty-six specimens subjected to microscope study, suggests that, on the average, not more than 3 to 5 per cent of the porous material represents cerussite and/or its leached equivalents. In other words, not more than 15 to 25 per cent of the lead originally present as galena is precipitated as cerussite within the cellular boxworks.

This is the more surprising, because not only is calcite an abundant gangue mineral in the Northern orebody, but other lime-bearing minerals, rare or absent in the Southern orebody, are not uncommon. For example, bustamite (a lime-bearing species of rhodonite) is general in the Northern orebody but not in the Southern. Furthermore, the cellular material itself carries an excess of readily-available neutralizer, as shown by the analyses of Table 1.

Thus, any hypothesis advanced to explain the lack of appreciable anglesite formation, must explain at the same time the small percentage of cerussite precipitated within the cellular material, in an environment of admittedly effective neutralizing power.

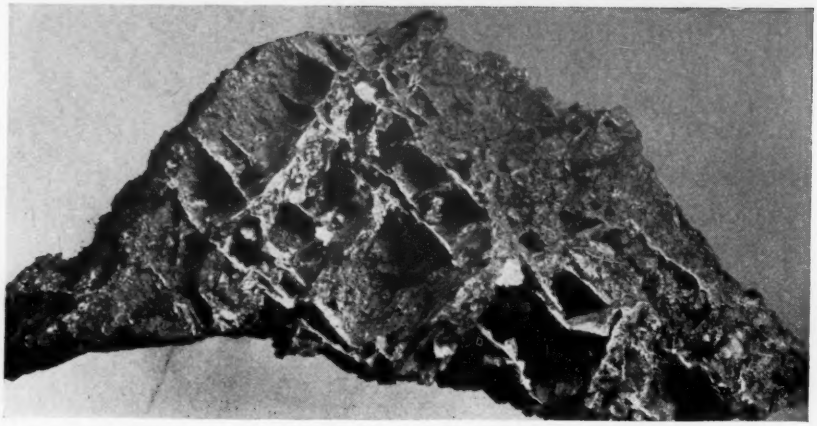

FIG. 12. Cellular boxwork derived from finely granular fluorite. Despite granularity of some of the Broken Hill fluorite, causing it to resemble loaf sugar in texture, a "cleaved" fracture pattern commonly develops during decomposition, similar to that within the massive crystalline fluorite nodules; usually the pattern is coarser, and cell walls are more profusely coated with supergene gangue carbonate granules that with well formed crystals. 2000-ft. level, 8th floor, section 18 stope, Southern orebody. $\times 1.6$.

6. Conditions enumerated in (4) and (5) above suggest that the sulphide leaching may not be accomplished by sulphate solutions; that the $SO_3$-rich mine water, noted in the analysis, neither originated within nor was derived from the specific patches or areas of leaching; and that the waters of the leached areas must carry $CO_2$.

But if mere dominance of $CO_2$ tends to inhibit formation of anglesite, an explanation is required for lead-zinc districts in limestone [15] (in which concentration of $CO_2$ in the solutions may be presumed to be at a maximum) where anglesite is a common mineral, not infrequently surrounding the galena nodules as a coating upward of one-fourth inch thick. An explanation also must be forthcoming as to why preferential leaching of galena over zinc sulphide is not, as at Broken Hill, the characteristic and prevailing condition in the limestone lead-zinc districts.

Even granting that the particular concentration of $CO_2$ in the solutions at Broken Hill may have prevented appreciable formation of anglesite, an explanation still is necessary for the low percentage of cerussite precipitated within the leached material at that place. At Mount Isa, for example, where carbonate gangue minerals (dolomite, ankerite, manganiferous siderite, calcite) within the shale gangue constitute 16 per cent of the silver-lead-zinc orebodies, cerussite accounts for 90 per cent of all oxidized lead minerals. Most of this cerussite is not a precipitate resulting from transportation of lead in solution, but is deposited essentially in place as the oxidized equivalent of the leached galena or anglesite.

Far too little is known about the multiform factors which may affect the decomposition of sulphides in an orebody containing complex sulphide and gangue intermixtures. Also, possibly far too much of our thinking is based upon theoretical considerations which are the outcome of experiments involving only one variable at a time. Allowing for such defects in our current thinking, it

[15] Such, for example, as Park City and Tintic (Utah), Leadville (Colorado), and the various lead-zinc mines in the Tri-State and Mississippi Valley districts, and in the limestone regions of Mexico.

still is difficult to explain satisfactorily the leaching phenomenon at the North mine.

7. However, a consideration of the above conditions leaves no doubt that failure of the galena, upon decomposition, to yield appreciable amounts of anglesite as a protective coating, is a vital, though probably not the only, factor in rapid leaching of the lead sulphide.

In this connection it may be noted that more than one metallurgist has been shocked to learn that a geologist can conceive of marmatite oxidizing more rapidly than galena. The metallurgist's conception of oxidation is the production of a surface film of high nuisance value metallurgically, rather than emphatic leaching.

Therefore, it would seem that despite a rather general impression among geologists to the contrary, the leaching of galena does proceed in nature with much rapidity in some noteworthy instances, and not merely in the case of isolated nodules, but for entire major districts.

For what it is worth, one suggestion is offered to explain why the protective coating of anglesite may be precluded from or strongly impeded in forming. At Mount Isa thorough leaching of pyrite and pyrrhotite (ratio 4:1) commonly extends 20 to 30 feet below the base of galena oxidation, and leaching of sphalerite [16] usually precedes the leaching of either pyrrhotite or pyrite. But nodules and seamlets of galena persist, in diminishing degree upward, nearly to the surface through a 180-foot depth of otherwise completely oxidized zone. Such galena almost invariably has a protective coating of anglesite.

However, in their microscopic study of Mount Isa ore, Grondijs and Schouten [17] noted that although the condition above stated is the general and preponderant one at Mount Isa, nevertheless where the pyrite-pyrrhotite content is low, the galena undergoes decomposition more readily than does the sphalerite.

[16] At Mount Isa the zinc sulphide carries 0.075 per cent isomorphous Fe to each 1 per cent of Zn, or about one-half as much isomorphous Fe as does the zinc sulphide at Broken Hill.

[17] A study of the Mount Isa ores. ECON. GEOL., June–July, 1937, page 435.

This suggests that certain, probably low, concentrations of acid in the leaching solutions constitute at least one, and possibly an important, factor in rapid removal of the initial oxidation film which so readily forms upon exposure of galena to the normal air-water oxidation processes.

It suggests further that the concurrent presence of $CO_2$ in the solutions, possibly over a limited range of concentration, may constitute another and perhaps vital factor. In many instances on field evidence, $CO_2$ to the point of saturation or near-saturation does not appear to preclude the formation and precipitation of anglesite, as in the limestone districts. It does not necessarily follow that in other circumstances at lesser concentration, in which $CO_2$ is weaker but still dominant in the solutions, may not retard or inhibit precipitation of anglesite as a galena coating. Such field evidence as the authors have collected through personal observation lends a certain amount of support to the latter supposition.

On the other hand, because the lead minerals as a whole show preferential leaching over the zinc minerals as a whole at Broken Hill, it seems probable that other factors than special concentrations of acid, and/or of $CO_2$ in the leaching solutions may play a part.

So far as the authors are aware, little experimental work has been carried out to test even the first of these assumptions. Possibilities are indicated for further fruitful laboratory investigation into the relative solubilities of the various lead and zinc minerals in other than normal aqueous solution.

For purposes of record, average percentages of the four major sulphides in the North mine at Broken Hill, and in the major silver-lead-zinc orebodies at Mount Isa, are furnished below:

| | Average Ore North Mine Broken Hill % | Average of the Three Major Ag-Pb-Zn Orebodies, Mount Isa % |
|---|---|---|
| Galena | 20.5 | 9.9 |
| Marmatite or sphalerite | 20.0 | 15.7 |
| Pyrite | undifferentiated 3.0 | 12.4 |
| Pyrrhotite | | 3.1 |

## SUGGESTED CAUSES FOR MORE EXTENSIVE LEACHING IN THE NORTHERN OREBODY.

As previously noted, leaching in the Southern orebody is far less extensive than in the Northern; for the levels herein discussed its average probably is not more than one one-hundredth as great. Such leaching as has taken place in the Southern orebody is confined more specifically to fluorite, with attack upon the galena and marmatite usually only incipient.[18]

Extensive and preferential leaching of the fluorite is comprehensible, because of that mineral's abundance in the Southern orebody and its established vulnerability to supergene attack. Reasons for the restricted total leaching within the Southern orebody limits are less apparent.

The hypothesis of possible lesser shattering is ruled out because the Southern orebody is somewhat more marked by well-defined faulting than is the Northern.

The only explanation which the authors have found plausible, and which they admit is not wholly satisfying, is one tied up with the time factor, expressed in the level development policy pursued at the North mine.

Broken Hill ore ground is notoriously "heavy," and in many places is difficult to keep open for protracted periods. Speed in development and extraction in a given section of ground thus becomes fundamental. Since the Southern orebody is nearest the operating shafts, it is opened up first and extraction carried out as rapidly as possible, whereas work upon the more distant Northern orebody on the same level is purposely delayed as long as possible.

Under such conditions complete, or nearly complete, drainage may be effected in the Southern orebody, and the circulation of ground water through it (at and above the level in question)

[18] The leaching phenomenon has been confirmed sufficiently by mapping to assure that the conditions set forth for the 2000- and 2150-ft. levels hold good in a general way for the Southern orebody from the 1100- to the 2600-ft. levels, and for the Northern orebody from the 1550- to the 2300-ft. levels. Elsewhere most portions of the mine have not been accessible for observation.

brought more or less to a halt within a short period. On the other hand, such evidence as is available suggests that at Broken Hill the hydrostatic head in outlying ground maintains a fairly steep gradient until the fractured area in question is actually penetrated (Fig. 8). Most of the Northern orebody at a given elevation therefore may remain beneath the water table from one to several years longer than the Southern.

Conjecture necessarily enters at this point, but it is not impossible that under such conditions, on a given level, oxidation and leaching within the Southern orebody may be brought virtually to a halt through more or less complete cessation of ground water circulation within its limits. At the same time in the Northern orebody, both oxidation and leaching may be actively stimulated by continuous downward "pull" of the circulating solutions toward the shaft sump (Fig. 8) as the much slower dewatering takes place.

Thus, in one case the early oxidation and leaching may come more or less to a standstill after an initial beginning which has had time chiefly to affect the abundant and vulnerable fluorite. In the other case from one to several additional years of more than normal acceleration to the process may prevail, and may not only greatly augment the total amount of leaching for that section of ground, but be instrumental in vigorously attacking the more slowly-reacting galena and marmatite. In this connection it is of interest to note that at the northern end of the Southern orebody on the 2150-ft. level, where development and stoping were delayed longest, there was noticeably more oxidation and leaching.

The above explanation seems to the authors the most plausible one, consistent with known facts, to account for the pronounced inequality of leaching within the respective Southern and Northern orebodies. The explanation is offered with a full realization that in part it rests upon conjecture, and that even so it is not entirely satisfying. Observations extending over a longer period of years, and over a greater number of levels, may be needed before the full explanation for such unequal leaching is revealed.

ACKNOWLEDGMENTS.

Acknowledgments are due A. B. Edwards for careful analytical and microscopic determinations in connection with supergene constituents of the cellular boxworks, and for criticism and suggestions in planning the paper; and to George Tunell for certain information concerning the leaching phenomenon relating to fluorite. Recognition of the antecedents of fluorite boxwork at Broken Hill was first made by J. R. Adam.

## APPENDIX.

### *Description of Boxwork Derivatives of Fluorite.*

At Broken Hill the cellular pseudomorph yielded by decomposing fluorite is often wholly surrounded by only slightly altered massive galena and marmatite, as in Fig. 11. To the unaided eye, the product bears superficial resemblance to galena's "cleavage" boxwork when it is lightly coated with "partially sintered" limonitic crusts.

Those features led to confusion in interpretation of the fluorite derivative when the product was first observed in connection with the present investigation. However, the fluorite derivative possesses distinguishing characteristics which serve to differentiate it from leached products of other origin. An attempt is made herewith to define the characteristics.

As noted in the paper, fluorite at the North mine occurs as: (1) a coarsely crystalline variety with strong cleavage faces, in masses up to 6 in. across; (2) a less common granular variety, with texture resembling loaf sugar, also in masses up to 6 in. across; (3) disseminated grains 1 to 3 mm. across.

In decomposition of the coarsely crystalline variety the initial webwork which eats its way along cleavage or fracture planes usually consists of limonitic jasper, but in some instances is composed entirely of supergene gangue carbonate. Its thickness rarely exceeds 0.01 mm.

As more of the fluorite goes into solution the webwork increases in growth and thickness, partly through replacement by

gangue carbonate of the limonitic rib where the latter is present, but mainly by coating the rib with aggregates of additional supergene gangue carbonate crystals or granules. Only rarely does limonitic jasper constitute an important ingredient of the boxwork after its initial penetration into the fluorite. Final cell wall thickness when all fluorite has been leached may be 0.5 mm. Usual thickness is 0.1 to 0.25 mm.

A frequent distinctive form of the thickened boxwork has incrustations of minute supergene carbonate gangue crystals upon the web. These are in closely packed formation like stacked cordwood, growing out into cellular space in both directions at right angles to the central web. Individually such crystals may be from 0.02 to 0.2 mm. long. The cordwood type of crystal packing has been observed thus far in the Leached Outcrops investigation only in fluorite derivatives, and is most common in boxworks which originated along cleavages of the coarsely crystalline variety.

Under any condition of oxidation the more strongly-formed and best-knit boxworks are those derived from crystalline fluorite. Their cell diameter rarely exceeds 1/10 inch. Characteristic types are illustrated in Figs. 9 and 10.

In granular fluorite the boxwork forms much as in the well-crystallized variety, and comprises the same intergrowth of limonitic jasper and gangue carbonate along the ribs, with supergene gangue carbonate coatings. The boxwork structure, however, is much coarser and more loosely-knit, with cell diameter frequently exceeding ½ inch. Also, the cordwood type of crystal packing is less in evidence, and the boxwork walls are more likely to be loosely coated with stubby crystals of the supergene gangue carbonate, or with shapeless granules of that composition. Typical boxwork derived from granular fluorite is illustrated in Fig. 12.

The coarser boxwork structure develops in the case of granular fluorite because, in the absence of well-defined crystal faces, the ribs or webs tend to follow an inherent cleavage pattern which appears to exist within the granular mass, even though it is not

TABLE 3.

MINERALOGICAL COMPOSITION (PERCENTAGE) OF THREE BROKEN HILL (NORTH MINE) DECOMPOSING FLUORITE SPECIMENS.

| | Pb. | Zn. | Cu. | As. | Fe. | Mn. | S. | $SO_3$. | F. | $Al_2O_3$. | $SiO_2$. | CaO. | MgO. | $CO_2$. | Calculated O. | Total. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. 1 | nil | nil | nil | 0.013 | 1.2 | 3.2 | 0.02 | n d | 43.9 | nil | 0.2 | 63.7 | 0.4 | 2.6 | | |
| Fluorite | | | | | | .4? | | | 43.9 | | | 45.48* | | | | 89.78 |
| Arsenopyrite | | | | .013 | .01 | | .006 | | | | | | | | | .029 |
| Pyrite | | | | | .01 | | .014 | | | | | | | | | .024 |
| Supergene carbonate gangue | | | | | .60 | 2.1 | | | | | | | .4 | 2.6 | .78 | 6.58 |
| Limonitic jasper† | | | | | .58 | .7 | | | | | .2 | | | | .66 | 2.14 |
| Miscellaneous | | | | | | | | | | | | | | | | 1.447 |
| | | | | .013 | 1.20 | 3.2 | .020 | | 43.9 | | .2 | 63.7 | .4 | 2.6 | 1.44 | 100.000 |
| No. 2 | nil | 0.3 | nil | 0.02 | 1.1 | 3.8 | 0.05 | n d | 42.7 | n d | 0.3 | 63.3 | 0.3 | 4.4 | | |
| Fluorite | | | | | | | | | 42.7 | | | 44.62* | | | | 87.32 |
| Arsenopyrite | | | | .02 | .015 | | .01 | | | | | | | | | .045 |
| Pyrite | | | | | .035 | | .04 | | | | | | | | | .075 |
| Smithsonite | | .3 | | | | | | | | | | | | .2 | .07 | .57 |
| Supergene carbonate gangue | | | | | .55 | 3.47 | | | | | | .83 | .3 | 4.2 | 1.16 | 10.51 |
| Limonitic jasper† | | | | | .50 | .33 | | | | | .3 | | | | .40 | 1.53 |
| | | .3 | | .02 | 1.100 | 3.80 | .05 | | 42.7 | | .3 | 63.3 | .3 | 4.4 | 1.63 | 100.050 |
| | | ZnO. | | | FeO. | MnO. | | | F. | | | CaO. | MgO. | $CO_2$. | | Total. |
| No. 3 | | 1.10 | | | 10.45 | 14.80 | | | 14.23 | | | 36.82 | nil | 28.85 | | |
| Fluorite | | | | | | | | | 14.23 | | | 14.87* | | | | 29.10 |
| Smithsonite | | 1.10 | | | | | | | | | | | | .60 | | 1.70 |
| Supergene carbonate gangue | | | | | | | | | | | | | | | | 69.39 |
| Siderite | | | | | 10.45 | | | | | | | | | 6.38 | | |
| Rhodochrosite | | | | | | 14.80 | | | | | | | | 9.19 | | |
| Calcite | | | | | | | | | | | | 16.00 | | 12.57 | | |
| Excess | | | | | | | | | | | | | | .11 | | .11 |
| | | 1.10 | | | 10.45 | 14.80 | | | 14.23 | | | 36.82 | | 28.85 | | 100.30 |

* Calculated as Ca. † Excludes adsorbed and capillary water and water of crystallization.

visible in the fresh rock.[19] The inherent cleavage pattern does not usually express itself through boxwork formation at such close intervals as is the case in distinctly crystalline fluorite.

Dominance of supergene carbonate gangue matter in the boxworks' composition is shown by the analyses of Table 3. In that table, the first two specimens represent successively advancing stages during the early decomposition of essentially pure fluorite. The third specimen represents the condition after decomposition is more than two-thirds complete.[20]

Because the boxwork structure so frequently patterns itself after the cleavage of fluorite, irrespective of whether the parent mineral was crystalline or granular, it may develop more or less parellelism of cell orientation, with well defined cross ribs. The structure thus may be mistaken for "cleavage" boxwork of galena origin, and the illusion may be heightened through a superficial resemblance, to the unaided eye, between the stubby crystals and granules which coat cell walls of the fluorite product, and the "partially sintered" limonitic crusts of cerussite origin which often encrust "cleavage" boxwork of galena origin. Compare, for example, the structures in Figs. 2 and 11.

In the fluorite derivative, however, the cross structure invariably makes an obtuse angle with the longitudinal rib, presumably reflecting the strong tendency of fluorite toward octahedral cleavage. The longitudinal ribs, likewise, never maintain strict parallelism, as do those in the galena derivative (Figs. 9 and 11).

Those features, together with the great predominance of supergene gangue carbonate crystals and their frequent stacked-cordwood pattern, serve to differentiate the fluorite-derived boxworks from cellular derivatives of other origin.

North Broken Hill Limited,
Broken Hill, New South Wales.
Mount Isa Mines Limited,
Mount Isa, Queensland.
*May 13, 1942.*

[19] A pattern of similar origin often is observed in the weathering of granular limestone, where a siliceous rhombohedral rib pattern not infrequently forms even though only grandular material is visible in the parent rock.

[20] Analysis of No. 3 specimen by A. B. Edwards.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1.10 | | 10.45 | 14.80 | | 14.23 | | 36.82 | 28.85 | 100.30 |

* Calculated as Ca. † Excludes adsorbed and capillary water and water of crystallization.

# MANGANESE-BEARING VEINS IN SOUTHWESTERN VIRGINIA.[1]

ANNA I. JONAS.

ABSTRACT.

Veins carrying manganese silicates largely in the form of the manganese garnet, spessartite, occur in the crystalline schists and gneisses of Carroll and Grayson Counties, Virginia, in the southern parts of the Galax and Independence quadrangles just north of the North Carolina State line. This brief paper includes a discussion of these manganese-bearing veins which are described in a report on the Geology and Mineral resources of the Great Gossan Lead district prepared by G. W. Stose and the writer for publication by the Virginia Geological Survey.

THE manganese-silicate area is a belt in the Blue Ridge Plateau that lies between the Blue Ridge on the southeast and the Iron Mountains on the northwest. The general upland surface of the plateau ranges from 2,500 to 3,000 feet in altitude and streams have trenched their channels 300 to 500 feet into the upland. New River flows northeast across this part of the plateau. In the vicinity of the manganese-silicate veins more or less rounded hills or knobs rise above the level of the plateau to a maximum altitude of 3,200 feet, while to the north higher mountains of the Point Lookout-Buck Mountain group project above the plateau surface to an altitude of 4,600 feet.

The manganese-bearing veins occur in two belts, in both of which the veins trend southwest following the structural trend of the country rocks. (Fig. 1.) In the southeastern belt they are in the Lynchburg gneiss and associated narrow bands of hornblende gneiss which are of later pre-Cambrian age. These rocks have been closely folded and metamorphosed and the crests of the folds have been sheared out along most of the zones of movement in the area. The veins in the northwestern belt are in a series of

[1] Published by the permission of the State Geologist of Virginia.

injection gneisses and granitic rocks of earlier pre-Cambrian age. These rocks were deformed during the northwestward movement on the Fries overthrust, which occurred at the same time as the folding of the Lynchburg gneiss. The mineralized zone parallels this thrust. The Great Gossan Lead, a copper-bearing pyrrhotite body, occurs in the Lynchburg gneiss between these two belts of manganese-bearing veins and trends parallel to them.

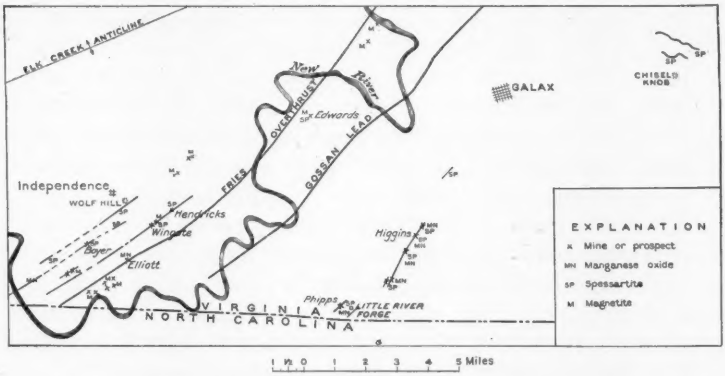


FIG. 1. Spessartite veins in the Great Gossan Lead District, Virginia.

*Southeastern Belt.* Veins of massive spessartite garnet occur in the Lynchburg gneiss and the hornblende gneiss intrusive in it in two areas; one in Grayson County 4 miles southwest of Galax, and the other in Carroll County 6 miles east of Galax. The longest vein lies southwest of Galax, where it can be traced for a distance of 3 miles on a low terrace whose surface is 2,500 to 2,600 feet in altitude, about 50 feet above and to the northwest of a road along Beaver Creek. The vein strikes N. 60° E., parallel to the strike of the foliation of the Lynchburg gneiss, and lies at the contact of the Lynchburg with a thin layer of hornblende gneiss. It dips 80° SE., with the country rocks. The vein rarely crops out on the surface and can be traced only by the presence of mine pits and dumps and surface float of glassy

quartz stained black by manganese oxide. A nearly barren quartz vein that can be traced only for a short distance forms the northeast end of the vein. Near the southwestern end it is closely paralleled by another shorter vein that lies to the northwest. A mile and a half southwest of the termination of the main vein the presence of two other spessartite veins still farther to the northwest is indicated by float and prospect pits.

The northeastern part of the main vein is on the property of Fontaine Higgins, where it was mined many years ago. In 1941 the Virginia Manganese Corporation of Richmond, Virginia, took an option on the property and sank a shaft to a depth of 40 feet. This shaft and more shallow pits to the southwest recently opened by the Binkley Coal Company of Chicago, Illinois, were helpful in the study of the mineralogy and extent of the veins and their relation to the country rocks. On the Higgins property, hornblende gneiss forms the footwall and mica schist of the Lynchburg gneiss forms the hanging wall. The vein as exposed in the shaft has a maximum width of 4 feet, and in places it pinches to 3 feet. The orebody visible in the shallow pits to the southwest is of about the same width but is more lenticular and less continuous and in places pinches out in the country rock.

The vein is composed of fine-grained, dense, dark-red spessartite garnet ($3MnO$, $Al_2O_3$, $3SiO_2$), that resembles in texture a fine-grained quartzite but is much heavier. It breaks along straight partings, in places filled with quartz. The massive spessartite contains nodular masses of glassy quartz and has cross-cutting veins of white and black glassy quartz with crystals of light-pink spessartite, fibers of light-green hornblende, and scanty grains of fluorapatite. The spessartite in the quartz veins is in euhedral crystals rarely exceeding 5 mm.

The partings in the massive spessartite and spessartite in the quartz veins are coated with thin films of black manganese oxide to the bottom of the 40-foot test shaft. Near the surface the oxidation of massive spessartite and of the spessartite in the quartz veins is greater. The hanging wall of mica schist is weathered and its surface next to the vein is slickensided and

coated with manganese oxide. The schist contains small knots of manganese oxide replacing it for a distance of 1 to 2 feet from the main vein. Near the surface fine-grained hornblende gneiss that forms the footwall is weathered and barren of ore, but near the bottom of the shaft where it is fresh it contains unoxidized grains and thin stringers of spessartite.

The mineralogy of the vein exposed in the pits to the southwest is the same as that described in the shaft at the Higgins property.

Vein quartz containing black tourmaline crystals occurs in float near the prospects and crops out to the southeast across the strike in a cut on the road along Beaver Creek. These quartz veins, 4 to 6 inches wide in mica schist, strike northeast with the schist and dip southeast at a less angle than the foliation. The quartz and tourmaline are coated and infiltrated with manganese oxide. Analysis of the tourmaline showed that it was not manganese-bearing, hence the manganese oxide with the tourmaline vein was probably derived from the weathering of grains of spessartite or other manganese-bearing minerals not seen in the weathered vein.

Muscovite pegmatite veins 1 inch wide and containing tourmaline needles cut the mica schist adjacent to the spessartite vein exposed in a tunnel at the southwest end of the Higgins vein.

A prospect pit dug by the Binkley Coal Company on the Otto Phipps land, southwest of the Higgins tract, lies one mile northwest of the strike of the main vein. It is located on a hill top at an altitude of 2,600 feet. The vein and the Lynchburg gneiss, which is the country rock, strike N. 55° E. The pit was 6 feet deep and showed a lenticular vein of spessartite with a maximum width of 3 feet. Fresh massive spessartite with only a thin film of oxide on parting planes extends to the surface. Thin veins of quartz with spessartite grains and hornblende fibers cut the vein.

Two miles northeast of the Higgins property, along the strike of the spessartite vein, a quartz vein containing manganese oxide and pyrite was opened in a small prospect in 1933. The vein lies at the contact of Lynchburg gneiss and hornblende gneiss. Farther northeast along the strike, a thin quartz vein stained black with manganese oxide crops out in a road cut of State Highway 89, 2 miles south of Galax. A quartz vein with tourmaline oc-

curs also on this road just south of Galax. Both are in Lynchburg gneiss.

Six miles east of Galax two parallel veins of spessartite with quartz vein cross Crooked Creek north of Chisel Knob. Blocks of quartz and spessartite, thinly coated with manganese oxide, and scattered outcrops of the vein occur for a distance of 2 miles along the strike of the north vein. It follows a thin layer of closely folded hornblende gneiss which strikes N. 70° W. in that area. In surface exposures of the gneiss, narrow veinlets of spessartite with quartz and epidote follow the contorted layers and both spessartite and gneiss are unweathered.

Twelve miles southeast of Galax in Surry County, North Carolina, a vein of spessartite garnet occurs in schistose Lynchburg gneiss. The vein is exposed in the mine of the Tar Heel Manganese Co., formerly operated by R. A. Freeman, and is located in the Piedmont Plateau about 3 miles south of the Virginia line where crossed by the Blue Ridge front. When visited by the writer in 1941 the largest pit was an open trench from which the ore had been removed for a distance of about 500 feet along the strike and a width of 20 feet at the widest part. The trench contained water at a depth of 30 feet. A 4-foot layer of massive spessartite garnet veined with quartz was left on the footwall of the mine, and the spessartite had a thin coating of black manganese oxide. A narrower layer of spessartite left on the hanging wall showed little oxidation. It is reported that about 385 tons of high-grade manganese ore were shipped from this mine in 1917 and 1918. The country rock is weathered schistose Lynchburg gneiss. The vein strikes N. 45° E. with the foliation of the schist and dips 45° SE. The vein and the lineation of the schist pitch 35° SW. The mine dumps contained blocks of quartz with manganese oxide and massive spessartite coated with black oxide. Rhodocrosite was reported as occurring in this mine but the writer found none in place in the mine or on the dumps.

*Northwestern Belt.* Spessartite garnet occurs in Grayson County southeast of Independence (Fig. 1) along three parallel strikes in a zone about 1½ miles wide. This belt is 6 miles northwest of the spessartite veins just described along Beaver

Creek. The spessartite southeast of Independence occurs in granite gneiss and augen gneiss lying on the southeast border of the Elk Creek anticline, just northwest of the Fries overthrust. The rocks of the Elk Creek anticline are largely biotite gneiss, diorite, granite, and injection gneiss of earlier pre-Cambrian age. They have been deformed and foliated during the movement on the Fries overthrust that has overridden the southeast flank of the anticline. The rocks of the injection complex are mylonitized along the thrust in a zone more than a mile wide.

The spessartite veins strike N. 45° E., parallel to that of the foliation of the gneisses and dip 30 to 35° SE. with the foliation. The veins are not continuous for any great distance along the strike. The most southeasterly vein crosses the Wingate property and extends northeast into the Hendricks farm. It is composed of massive and finely granular spessartite, quartz, and actinolite. At the outcrops on the Wingate property it lies parallel and adjacent to a vein of crystalline magnetite and coarsely crystalline manganese-bearing pyroxene that belongs to the diopside-hedenbergite series. Magnetite from this vein was mined years ago on the Wingate property. On the Hendricks farm the presence of massive spessartite garnet is indicated by abundant float along the slope of a linear hill. The blocks of massive garnet contain also quartz with pyrite and massive light-gray epidote low in iron, nearly of the composition of zoisite.

A second vein of spessartite garnet that also contains hedenbergite occurs on the Boyer farm. A chemical analysis of hedenbergite from this place, made by the Federal Geological Survey, is given below:

ANALYSIS OF HEDENBERGITE, GRAYSON COUNTY, VA.

(J. G. Fairchild, analyst)

| | |
|---|---|
| $SiO_2$ | 49.26 |
| FeO | 19.65 |
| MgO | 2.11 |
| MnO | 3.56 |
| CaO | 21.88 |
| $Al_2O_3$ | 0.74 |
| $Fe_2O_3$ | 2.17 |
| $H_2O$ | 0.66 |
| | 100.03 |

Two miles to the southwest along this strike a quartz vein containing manganese oxide in cavities is exposed in a road cut. The vein is now porous, probably due to the weathering of a manganese silicate from which the oxide was derived. Three-fourths of a mile northeast of the Boyer farm a vein 2 feet wide crosses a sharp curve of U. S. Highway 21, 1 mile south of Independence. It dips 75° SE. and lies at the contact of hornblende gneiss and mica schist. The vein is composed of quartz with several 4 to 6 inch layers of finely granular spessartite garnet and contains grains of kaolinized feldspar and scanty actinolite blades. At the surface the garnet has largely weathered to manganese oxide. A short distance to the northwest spessartite occurs in another vein on the southwest side of Wolf Hill just south of Independence.

A prospect was opened for manganese oxide on the Elliott property lying along the Fries overthrust to the southeast of the spessartite veins in this belt just described. A trench 20 feet deep was dug northwest across the strike of the granite mylonite which dips 30° SE. The mylonite is replaced by brown ferruginous chert with drusy quartz lining small cavities. Tourmaline is present in the quartz. Manganese oxide coats some of the quartz grains and forms thin seams in the cavities, but no manganese silicate was found here. Manganese-garnet associated with veins of crystalline magnetite occurs along the zone of mylonitization that follows the Fries overthrust in Virginia, and is known for a distance of 20 miles to the southwest along the thrust in North Carolina. These veins have been prospected at several places in North Carolina but very little manganese oxide has been found.

Two and one-half miles south of the Virginia line and 7 miles southwest of the Higgins prospect, a manganese-bearing vein occurs in Alleghany County, North Carolina, on a strike somewhat northwest of the vein on the Higgins prospect in Virginia. It has been opened at Crouse Knob at an altitude of 3,000 feet on the southeast side of Bald Knob. The vein was explored by a shaft which had fallen in when visited by the writer in 1938.

The mineralogy of the vein was described in detail by Ross and Kerr.[2] They report that the vein is 5 to 7 feet wide. It strikes N. 50° E. and dips 50° SE. and lies along the contact of hornblende gneiss and Lynchburg gneiss. The chief manganese mineral is spessartite garnet, with rhodonite ($MnO$, $SiO_2$) as the second mineral of relative abundance. Manganese carbonate, rhodochrosite, occurs in the rhodonite. Tephroite, the manganese olivine ($2MnO$, $SiO_2$), and alleghanyite[3] ($5MnO$, $2SiO_2$) are in veins in the rhodonite. Galaxite, a black manganese spinel ($MnO$, $Al_2O_3$), occurs as black shiny grains intergrown with alleghanyite. The vein is distinctly banded, and spessartite forms massive lenses 2 feet in width, whereas rhodonite forms one lens 4 inches wide. The report by Ross and Kerr states that oxides of manganese are abundant to a depth of 10 feet and none were found below a depth of 40 feet. In 1941 the Binkley Coal Co. started to reopen the mine in the belief that manganese carbonate and oxide formed a large part of the ore, but abandoned it when they found the ore was largely silicates.

Rogers[4] also studied specimens of alleghanyite from the mine near Bald Knob and states that it contains the two volatiles, water and fluorine. He gives as the revised formula of the mineral, $2Mn_2.SiO_4.Mn(OH,F)_2$. He found also that alleghanyite is monoclinic and not orthorhombic, as stated by Ross and Kerr, and that the mineral is isomorphous with chondrodite. He reports the presence of alabandite ($MnS$) with galaxite in the alleghanyite. At Bald Knob a mineral succession of alleghanyite, tephroite, rhodonite, and spessartite in order of the decreasing ratio of manganese to silica is suggested. Rhodonite probably was followed by alabandite and rhodochrosite. The presence of the two volatiles in alleghanyite may throw doubt on the position of that mineral in the succession. The fact that alleghanyite and

[2] Ross, C. S., and Kerr, P. K.: The manganese minerals of a vein near Bald Knob, N. C. Amer. Min., 17: 1–18, 1932.

[3] Alleghanyite and galaxite are new minerals named in the article by Ross and Kerr.

[4] Rogers, A. F.: The chemical formula and crystal system of alleghanyite. Amer. Min., 20: 25–35, 1935.

tephroite occur as veins in rhodonite, as reported by Ross and Kerr, seems to indicate that both these minerals may be later than the rhodonite.

Although the manganese-bearing vein at Crouse Knob is but 2½ miles southwest of the manganese silicate veins in southwestern Virginia, none of the manganese minerals that occur with spessartite at Crouse Knob were found with the spessartite in the Virginia occurrences.

Veins of spessartite garnet have been exposed by recent exploration of the North Carolina Manganese Co. of Raleigh, North Carolina. They are in the eastern part of Wake County, 3 miles east of Zebulon, North Carolina. The area is on the western border of the Coastal Plain sediments, and a gravel cap about one foot thick overlies slates of the "Virgilina volcanic series" in which the spessartite veins occur. The prospect pits opened in 1940 expose 3 to 5 parallel vertical veins striking N. 15° E., parallel to the cleavage of the slate. The veins are 1 to 4 feet wide, separated by narrow bands of clay derived from weathered slate, and extend for about 1,000 feet along the strike. They were trenched across the strike at intervals of about 50 feet to an average depth of 2 to 6 feet, with one trench 20 feet deep. The manganiferous belt swells to about 25 feet wide in the center and pinches to less than 5 feet at the ends.

The float ore is quartz and wad or psilomelane. The veins, where exposed by trenching, show fine-grained, massive spessartite thinly coated with black manganese oxide. The spessartite is cut by vein quartz and streaked with pyrite. Near the surface the spessartite has been oxidized on parting planes, but even there the oxidation zone is very thin, and at shallow depths the oxide appears to pass into unweathered garnet, hence only a small tonnage of oxide is available.

*Oxidation of the Ores.* Weathering in most crystalline rocks takes place slowly and is deepest on land surfaces that have stood at a constant level for a long period of time. Spessartite garnet is especially resistant to weathering. In the veins examined, weathering of the silicate to manganese oxide has taken place from

the surface downward along closely spaced partings that are chiefly parallel to the schistosity of the country rock. The amount of oxide formed decreases with depth. It is very scanty at a depth of 40 feet, which is the lower limit of exploration in the Virginia and adjoining North Carolina area. Blocks that appear to be solid manganese oxide have a core of unaltered dark-red garnet that can be recognized only on a freshly broken fracture. The oxide in most cases is only a thin film on unaltered silicate.

The terrace surface in southwestern Virginia near Beaver Creek, where manganese ore has been prospected, stood at a fixed level for a considerable time, hence on the terrace surface there is a fairly good showing of manganese oxide in the vein. The terrace surface is not continuous along the vein, but, has been cut into by cross drainage that flows southeast into Beaver Creek. In these cross valleys, cut 40 to 60 feet below the terrace level, little manganese oxide occurs and the exposed vein is largely spessartite. The veins north of Chisel Knob lie on the drainage slope of Crooked Creek, and there the garnet is largely unoxidized because the creek has removed the old terrace surface, where oxidation of manganese garnet probably took place before the present erosion cycle began.

Manganese oxide has been prospected and mined in the belts near Galax and Independence, but for the following reasons, only a small amount of ore has been obtained: the deposits of oxides are shallow because they lie in the Blue Ridge Plateau where the rocks are not deeply weathered, and the spessartite garnet, from which the oxide was derived, is even less weathered; the residual oxide is limited in occurrence to erosional remnants of the plateau and terrace surfaces; and the silicate ore occurs as lenses and not as continuous bodies. The relatively large amount of oxide found and removed from the mine of the Tar Heel Manganese Co. in adjoining North Carolina is due to its location in the Piedmont Plateau where the rocks at the surface are more deeply weathered than those on the Blue Ridge Plateau because the Piedmont lies 1,500 to 1,800 feet lower and has been subject to less erosion since peneplanation than the higher plateau.

Because of the small amount of marketable oxide that so far has been found in the silicate veins of the Blue Ridge Plateau these veins and other silicate deposits in areas of shallow weathering are not now a commercial source of manganese. They may be a potential source of manganese if a method can be found to treat the silicates and extract the manganese.

*Genesis and Age of the Ore Veins.* The manganese deposits in southwestern Virginia and adjoining parts of North Carolina occur in pre-Cambrian crystalline rocks and are derived from the oxidation of manganese silicates. Because of their manner of occurrence and mineral association the writer believes that the manganese silicates of that area are of hydrothermal origin.

Other theories of origin have been advanced for manganese silicate deposits in pre-Cambrian rocks elsewhere. In India manganese-bearing silicates occur widely in pre-Cambrian rocks of two ages. In the older Archean rocks manganese silicates, largely spessartite, occur with pyroxene and apatite. Fermor [5] describes this assemblage as a basic segregation in a quartz-feldspar intrusive. The oxide ores are believed to have been formed by concentration and replacement of the feldspathic rocks during a period of peneplanation. The ores in the rocks of later Archean age are described as having been deposited as oxide in a sedimentary series containing limestone; the oxides were metamorphosed to spessartite, rhodonite, and piedmontite, and later the oxide deposits were formed by oxidation of the silicate minerals accompanied by some replacement and concentration. Manganese silicates that occur in metamorphosed pre-Cambrian sediments of the Gold Coast, Africa, are believed [6] to have had a similar origin.

Several explanations have been suggested as to the origin of manganese ore in pre-Cambrian rocks in the State of Minas Geraes, Brazil. In 1901 Derby [7] stated that the dike-like masses of spes-

[5] Fermor, L. L.: Manganese-ore deposits of India. Geol. Surv. of India Mem., 37, part II: 236–389, 1909.

[6] Junner, N. R., and Kitson, Sir A. E.: Manganese ore deposits of the Gold Coast, Africa. A. I. M. E. Trans., 65: 394, 1927.

[7] Derby, A. O.: On the manganese ore deposits of the Queluz (Lafayette) district, Minas Geraes. Am. Jour. Sci., 1901, p. 18.

sartite which were exposed in shallow cuts, were magmatic segregations from a basic rock. Later Harder [8] reported that other observers believed that the silicates from which the manganese oxides were derived occurred as disseminated minerals in schists and limestone. The Morro da Mina mine, the largest in the area, is an open cut about 500 feet in depth. Hewett,[9] who visited the mine in 1942, stated that the oxide ore occurs in four vertical and parallel lenses in mica schist. The oxides pass in depth into manganese carbonate and silicates. Both Hewett and the mine geologist regard the ore bodies as a hydrothermal replacement of a bed of limestone which had been folded into isoclinal folds, thus repeating the replaced bed three times.

In southwestern Virginia, the Lynchburg gneiss does not contain disseminated manganese silicates and the ore is not associated with limestone beds nor with a particular horizon that might have originally contained manganese minerals. It is not believed that there the silicates were formed by metamorphism of manganiferous sediments or by concentration from such sediments. The manganese silicate occurs in lenses made up largely of massive spessartite, cut by manganiferous quartz veins. The connection of the lenses by quartz stringers was not observed. These veins occur along parallel strikes en échelon to each other and have entered the country rock along the foliation of the country rock which they parallel in strike and dip. Tourmaline, fluorapatite, magnetite, pyroxene, sulphides and other high temperature minerals accompany the manganese-silicates which are believed to be derived from hypogene solutions that penetrated the rocks along schistose planes. Manganese silicate replaces the country rock adjoining the vein only for a short distance. The manganese deposits near Bald Knob, at the mine of the Tar Heel Manganese Company, and at Zebulon, North Carolina, have a similar origin.

The manganese-bearing veins of southwestern Virginia and nearby North Carolina lie in a belt containing the copper-bearing

[8] Harder, E. C.: Manganese deposits of the United States. U. S. Geol. Surv. Bull. 427: 183–189, 1910.

[9] Hewett, D. F.: The Morro da Mina mine, Brazil. Paper read at Geol. Soc. Wash., April 1942.

pyrrhotite ore body of the Great Gossan Lead (Fig. 1) and mineralized quartz veins. Since 1850 the Gossan Lead orebody has been mined at many places for secondary copper ore, iron from the gossan cap, and primary sulphides. At present the General Chemical Co. mines sulphide ore at Iron Ridge, 4 miles northeast of Galax. Like the manganese-bearing veins, the Great Gossan Lead orebody is a series of lenticular [10] veins which has penetrated the country rock along foliation planes. At the Iron Ridge mine euhedral crystals of spessartite garnet are in the gangue and have replaced the Lynchburg gneiss near the orebody. Also, sulphides occur in the manganese-bearing veins. The deposition of manganese silicates, the copper-bearing pyrrhotite body and the mineralized quartz veins are intimately related to the structure of the rocks of the region. They are later than the regional deformation which took place in the late-Paleozoic orogeny. It seems evident that the manganese-bearing silicate veins as well as the associated mineralization were emplaced in the closing stages of that orogeny or soon thereafter.

The source of the ore solutions is not definitely known. The region contains muscovite-granite pegmatite that, like the ore veins, is not deformed. It intrudes the Lynchburg gneiss in small dikes near the spessartite veins of the Beaver Creek area. These dikes contain tourmaline. Quartz vein containing tourmaline in which the quartz and tourmaline are coated and infiltrated with manganese oxide crops out near the manganese-bearing veins. These facts indicate a common magmatic source for the pegmatite, quartz vein, and ore minerals. The pegmatite dikes are related to larger masses of undeformed muscovite granite that have intruded the Lynchburg gneiss and hornblende gneiss in nearby North Carolina to the southeast and southwest. It seems probable that the ore deposits here described were formed by emanations from the deep-seated masses of igneous magma from which the granite and pegmatite were derived and that the formation of the ore veins closely followed the granitic intrusions.

[10] Ross, C. S.: Origin of the copper deposits of the Ducktown type in the southern Appalachian region. U. S. Geol. Surv. Prof. Pap., 179: 44; 77–85, 1935.

Manganese silicate veins occur throughout the crystalline belt of the Southern Appalachians. Spessartite is the most common silicate found, but rhodonite and tephroite, as well as rhodochrosite, have been reported in some of the veins. Alleghanyite, so far as known, has not been found in the Southern Appalachians except at Bald Knob. In north-central Virginia manganese silicates were prospected or mined for manganese oxide at several places, including a mine 7 miles west of Spotsylvania Courthouse, mines in southern Louisa County south of South Anna River, and one in Fluvanna County one mile north of Central Plains. These veins are in the crystalline schists of the Glenarm series. The vein north of Central Plains replaces the Peters Creek quartzite of the Glenarm series and strikes N. 40° E. with the country rock. The ore vein is 10 feet wide and dips 35° SE. It is composed of massive light salmon-pink and deep reddish-pink rhodonite intersected by thin quartz veinlets. It contains thin layers of hematite, jasper, and actinolite with magnetite crystals and mottled with salmon-pink rhodonite. The oxides form only a thin film on the surface of the rhodonite and have penetrated it in cracks. The writer found no spessartite, although its presence has been reported there.

The veins of north-central Virginia, like those in southwestern Virginia, are localized in zones of shearing, are parallel to the foliation of the country rock, and are later than the major regional deformation which has been assigned to late-Paleozoic orogeny. The writer suggests that the source of the ore solutions in north-central Virginia also is the parent magma of nearby masses of undeformed granite, probably of late-Paleozoic age. Other ore-bearing veins, many of which carry gold,[11] occur in the general area. In an early report on the gold belt near James River, Taber [12] suggested a genetic relation between these granites and the gold-quartz veins. Park (p. 18) regards the relation as probable but as "not convincingly demonstrated."

[11] Park, C. F., Jr.: Preliminary report on the gold deposits of the Virginia Piedmont. Va. Geol. Surv. Bull., 44: 1–42, 1936.

[12] Taber, Stephen: Geology of the gold belt in the James River basin, Virginia. Va. Geol. Surv. Bull., 7: 216–217, 1913.

*Another type of Manganese deposits in the Virginia Piedmont.* Manganese deposits that have a different method of occurrence and genesis occur in the crystalline rocks of the Glenarm series in the Piedmont Province in Virginia. These deposits occur as oxides in calcareous quartzite beds of the Mount Athos formation [13] in a belt 60 miles long, extending from a point near Warminster, Nelson County, at the northeast, to Alta Vista on Staunton River in southern Campbell County at the southwest. Manganese oxide has been mined at many places along this belt since before 1900. The Piedmont Mine, one of the most productive of these manganese mines, located 6 miles southeast of Lynchburg, was described by Hewett,[14] who stated that the largest lens of manganese there was "formed by replacement of quartz-mica schist, possibly locally calcareous, by manganese minerals. The manganese has probably not been derived from the adjacent wall rocks for they are fresh—." He concludes that the deposit is of superficial origin formed by replacement of the schist during the formation of the early Tertiary peneplain on which the ore-bearing schist outcrops.

In the last few years mining activity has been revived in this belt, and G. H. Espenshade of the United States Geological Survey has recently studied the manganese deposits and geology of the entire belt. W. R. Brown of the Virginia Geological Survey also has mapped the part of the belt that is included in the Rustburg quadrangle.

The writer visited several of the recently developed mines in 1941 in company with Brown, Espenshade, and G. W. Stose. The manganese oxides occur in clay beds in calcareous quartzite of the Mount Athos formation, near its contact with crystalline limestone. The ores appear to have been concentrated by the replacement of the rock by manganese oxides derived from source minerals originally disseminated in the nearby sedimentary formations. An open cut in one of the mines exposed an alternation

[13] Furcron, A. S.: James River iron and marble belt, Virginia. Va. Geol. Surv. Bull., 39: 22–27; 104–109, 1935.

[14] Hewett, D. F.: Some manganese mines in Virginia and Maryland. U. S. Geol. Surv. Bull., 640–C: 49–54, 1916.

of thin quartzite beds and deeply weathered zones of manganiferous clay containing manganese oxides. This relation clearly suggested that the manganiferous beds now weathered to clay were originally calcareous sedimentary beds that contained disseminated manganese minerals and were interbedded with purer quartzite beds.

In mode of occurrence therefore these manganese deposits resemble the widespread deposits of manganese oxides formed [15] in calcareous beds of a similar type near the contact of the Antietam (Erwin) quartzite and the Tomstown (Shady) dolomite of Lower Cambrian age in the Appalachian Valley of Virginia and Tennessee. The age of the calcareous beds in which manganese occurs in these two areas is not the same, for the Mount Athos formation is a part of the Glenarm series of probable pre-Cambrian age. These deposits near Lynchburg, therefore, have been concentrated by circulating meteoric water near their stratigraphic source in sedimentary beds and are not in veins, as are the spessartite garnet deposits in southwestern Virginia and nearby North Carolina, in the north-central Piedmont of Virginia, and near Zebulon, North Carolina.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
*May 20, 1942.*

[15] Stose, G. W.: Source beds of manganese ore in the Appalachian Valley. ECON. GEOL., 37: 163–172, 1942.

# DISCUSSION AND COMMUNICATIONS

## *DIFFERENTIAL DENSITY OF GROUND WATER IN ORE DEPOSITION.*

*Sir:* The central idea of this paper [1] is that solutions that become heavily charged with mineral matter in the zone of oxidation of ore deposits are able, because of increased specific gravity, to settle through the lighter ground water of the underlying water-saturated zone so that secondary sulphide enrichment is not necessarily confined to a horizon near the water table but may extend indefinitely below the water table even in areas where artesian circulation is improbable. As partial evidence the author has cited the phenomenon, well known to ground-water hydrologists, of thick lenses of fresh ground water floating on salt ground water in coastal islands, the two classes of water maintaining a sharp separation owing to the difference in density.

The fundamental problem on which the proposed modification of the secondary enrichment theory must stand or fall is that of passing small masses of a heavier solution through a lighter solution without mixing the two at an early stage. This problem does not exist in the hydrologic set-up of the coastal islands. It has not been discussed by the author. I was at first very skeptical of the idea but I find that the problem has been considered as effective by the oceanographers and limnologists in its application to bodies of free water.[2]

[1] Brown, J. S.: Differential density of ground water as a factor in circulation, oxidation and ore deposition. ECON. GEOL., 37: 310–317, 1942.

[2] McEwen, G. F.: A mathematical theory of the vertical distribution of temperature and salinity in water under the action of radiation, conduction, evaporation and mixing due to resulting convection. Bull. Scripps. Inst. of Oceanography, Tech. Ser. 2: 197–306, 1929. See esp. pp. 199–202; Hutchison, G. E.: Limnological studies in Connecticut: Mechanism of intermediary metabolism in stratified lakes. Ecological Mono. 11: 21–60, 1941. See esp. pp. 34–35, role of density currents;

Small unit masses of water at or near the surface of a standing body of water may acquire a higher specific gravity by surface cooling, evaporation, or solution of mineral matter from littoral or sublittoral muds. These masses sink, either vertically through the free water or down the slope of the basin until they reach their specific gravity level in the density stratification that characterizes large standing bodies of water. There they spread out and lose their identities as separate units. The flow is laminar, and no turbulence is involved other than as an interfering condition.

If this mechanism will work in an open body of water, then the only additional factor involved in applying it to a body of ground water would apparently be the added effect of frictional resistance to equilibration of the unbalanced forces. From the fact that Darcy's law relating the velocity of ground water percolation to the slope of the water table is reported to hold for a hydrostatic gradient of only 2 or 3 inches per mile, this frictional resistance factor would appear to be negligible.

The whole problem is without doubt amenable to quantitative mathematical treatment as to what differences in specific gravity are necessary to overcome the frictional inertia (if any), the speed of settling for a given difference in specific gravity, and other quantitative aspects of the phenomenon. The mathematical analysis that has been applied to a body of free water involves differential and integral calculus, and application to a ground water mass would offer no simplification. I would not urge that the author rewrite his paper to include this mathematical analysis of his theory; it probably would be read and understood by few geologists. But until this is done his theory has only a qualitative standing. I believe that it will work, but I don't know to just what extent it will work. The mechanism might be so slow that it would have no practical bearing. Certainly as applied to known deposits formed by secondary enrichment the theory has not always been applicable, for there are examples in which the second-

pp. 36–40; for a text-book discussion of density stratification in lakes, see Welch, P. S.: Limnology. McGraw-Hill, 1935, pp. 43–66, esp. pp. 45–57.

ary sulphide body is fairly closely confined to a thin horizontal zone related to the present water table or an earlier water table. The principle can probably best be offered as a modification of the secondary enrichment mechanism that would in certain instances account for extensions of the secondary sulphide body for considerable distances below the water table. It would make unnecessary the usual assumption of artesian circulation at depth in response to unbalanced hydrostatic head.

EDWIN T. MCKNIGHT.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

## *BANDED HEMATITE ORES.*

*Sir:* Two discussions on the origin of banded-hematite ores, the first by myself, the second by Dr. Woolnough, appeared in recent consecutive numbers of ECONOMIC GEOLOGY—volume 36, Nos. 4 and 5.

It is interesting to note that we both regard the land surface, during formation of the deposits, as being highly ferruginous or even lateritic in character—the period was one of prolonged and deep oxidation. From this point we differ: Woolnough suggests that both the iron and silica were chemically precipitated as sediments in shallow lake basins, whilst the evidence in India suggests to me that the silica is secondary. The contrast is not without humor, for at the end of his discussion Woolnough refers to the possible magmatic (presumably secondary) nature of certain Australian deposits, whilst my contribution ends with a confession to having nothing against the sedimentary origin of the silica!

It was with some surprise that I realized Dr. Woolnough was advancing his suggestion as something new. Briefly his view is that the sediments were deposited in closed basins on a land surface reduced almost to base level and covered by "duricrust" (or laterite); he deprecates the supposed prevalent insistence in the literature on marine sedimentation. However, my experience in discussion with geologists in several countries, has been that they nowadays mostly take it for granted that the neighboring land surface

must have been highly ferruginous, or lateritic (how otherwise could the sedimentary iron have been derived!), and that deposition in lake basins was equally as likely as in the sea. As these features are fundamentally obvious one can well imagine most geologists remarking on them rather casually and implicitly including "sublacustrine" in "submarine" instead of using the inclusive term "subaqueous." For example, in 1936, I wrote:[1]

> . . . there is, in fact, no reason why the banded-hematite-quartzites could not have been deposited in a great lake basin. . . . The iron was transported either in the form of soluble salts, which may have been precipitated as hydrated ferric oxide or, in part, silicate, or, less probably, as carbonate, or as detrital ferrous silicate or even finely divided hematite. . . . For the most part silica was precipitated as chert from solutions, either brought in from the adjacent land surface . . . in an area covered by basic tuffs, subjected to prolonged weathering with probably the formation of a widespread cap of lateritic material, it is possible to picture the rivers taking away almost pure iron compounds. It is no more difficult to picture the accumulation of such a thickness of iron-bearing beds than it is to picture the deposition of a great thickness of pure sandstone, or of a thick bed of coal or of salt.

These views, similar to those of Woolnough, are not unusual, but come to mind at once if the sedimentary origin of the iron and silica is accepted. Although prepared to accept the sedimentary origin of many of these deposits, the evidence of those deposits which I have examined for so many years in India is in favor of the silica being secondary.

I would commend to Dr. Woolnough some of the literature on Indian laterites and bauxites—after all India is the "home" of the laterites, as they were first described by Buchanan Hamilton in South India in 1802. He will find that in India, as in other countries, the processes in the formation of laterite have been long described. Here, we may see laterite derived from rock types ranging from basic igneous rocks to granites, or from shales to quartzites. Even lateritic bauxite capping quartzite is not unknown.

We may summarize the conditions under which laterite forms:

[1] Dunn, J. A.: The mineral deposits of Eastern Singhbhum. Mem. Geol. Surv. India, LXIX: 207, 1937.

1. The dominant feature of laterite is, perhaps, that it occurs on an old land surface. The red soils so well known in many countries as typical of an old landscape, are just an incipient form of laterite. Laterite can only form where sheet erosion is slow. It commonly attains its greatest thickness around the edges of head erosion.

2. Oxidation of the rocks at the surface must be at a maximum.

3. Maximum conditions of oxidation are obtainable in tropical and sub-tropical climates; laterites are not found in temperate and arctic regions (the "duricrust" of Woolnough occurs in the hotter or subtropical parts of Australia; in the more temperate parts the nearest approach to ferruginous duricrust is the red soil of the Mallee in North West Victoria, or the "buckshot gravels" near Melbourne).

4. Although it is true that surface enrichment of iron can occur in areas of low annual rainfall, the *best* development of laterite, and bauxite, is in areas of quite high rainfall.

5. The rainfall must be markedly intermittent—periods of thorough soaking of the surface and subsurface must alternate with long hot dry periods, during which the water table rapidly falls and upward capillary movement with leaching below and deposition of colloidal material above is a maximum. Reh salts of India, and kankar or travertine form under similar conditions.

6. The thickness of the laterite tends to increase in the direction of slope of the water table. For example, on a plateau, the laterite tends to be thicker around the edge than in the center.

Thus the really essential facts are that laterite forms only in a region of intermittent heavy rainfall in which the climate is sufficiently hot to cause rapid evaporation of moisture at the surface. Abundance of iron and alumina is immaterial, sufficient is present in most rocks.

Peneplanation is not so necessary as Woolnough would suggest for the formation of laterite. Laterites are found covering (*a*) peneplains (*e.g.* the boundary between the coastal deposits and older rocks, Bengal, Bihar, and Orissa, India), (*b*) rolling or

even steeply undulating uplands (*e.g.* the Eastern Ghats in India up to elevations of 4,000 feet), and (*c*) plateaux bounded by strongly eroded scarps (*e.g.* the Deccan Traps of the Western Ghats, India, up to elevations of 5,000 feet). In every case these are old land surfaces, but lateritization is still proceeding to-day.

Woolnough's insistence on peneplanation as the principal factor in lateritization becomes drastically qualified when observations are extended to other countries, just as views on monsoonal influence in India must be qualified when Australian evidence is considered. The suggestion that the effects of peneplanation in Australia provide, perhaps, a more complete study than in any other part of the world, should, from my experience of that country, be qualified; they are beautifully illustrative of certain phases of peneplanation.

As Dr. Woolnough points out in his paper our understanding of geological phenomenon is largely governed by our personal environment and experience. The fact is well illustrated in his relating the origin of banded iron-ores to conditions of peneplanation comparable to those in Australia. I had hoped, when reading the paper, that actual evidence of such banded iron-silica deposits in process of formation today in the shallow Australian continental basins would be forthcoming. Until such actual evidence is provided, the picture remains as hypothetical as it always has been. For those deposits in which the silica and iron were clearly sedimentary, I would be in agreement with the conditions envisaged by Dr. Woolnough, except that such advanced peneplanation would not be essential, and that deposition in estuaries and coastal lagoons as well as lakes remains probable. Further, the derivation of the silica from submarine or sublacustrine springs is not necessarily improbable.[2]

[2] Dr. Woolnough suggests that the salt content of seawater would be a deterrent to the acceptance of marine deposition. But is there any justification for the assumption that the sea was of the same composition in Archean times as to-day? On any basis of logical deduction the sea must surely have been comparatively free from salts at first, but has since become more saline. Indeed, this very change deserves serious consideration in discussing the comparative uniqueness of banded hematite quartzites in early geological time.

Dr. Woolnough suggests that the absence of the banded iron-ores in periods later than the pre-Cambrian is explained by a presumed extreme rarity of periods of complete peneplanation in geological time. There is no real justification for this presumption, and, if they are related to peneplanation similar banded iron-silica sediments would have been deposited in some later periods of peneplanation. The conditions envisaged are scarcely less common than, say, those associated with the precipitation of sedimentary salt deposits, in fact the two show certain similarities. The fact of their rarity in time must be explained otherwise, and be related to some other phenomenon. One suggestion is coincidence in the outpouring of silica solutions from springs below a basement into which iron was being brought from the adjacent lateritized land surface. Or, may I point out that, on my hypothesis for the Indian deposits—the association of widespread and deep oxidation with volcanic activity, accompanied by silicification of fine-banded oxidized tuffs on the grand scale, under the action of ground waters heated by magmatic steam—the odds of coincidence would make this hypothesis more closely conformable with their rarity of occurrence in time. In such volcanic periods as that with which these deposits appear to be associated in many parts of the world, I see no objection to similar rock types being formed by more than one process. How many rock types in geology have had various modes of formation!

J. A. DUNN.

GEOLOGICAL SURVEY OF INDIA,
*March 9, 1942.*

# REVIEWS *

**Geology of the "Martic Overthrust" and the Glenarm Series in Pennsylvania and Maryland.** By ERNST CLOOS AND ANNA HIETANEN. Geol. Soc. America Spec. Pap. No. 35. Pp. 207; pls. 28; figs. 58. 1941.

This outstanding publication presents the results of what is probably the most intensive structural investigation of a considerable area that has yet been carried out in America.

Part I, (Cloos), consists of an exhaustive discussion of the structural geology and petrofabrics of southern Lancaster County, Pennsylvania, and of less detailed investigations of three smaller areas between the Susquehanna and Potomac Rivers.

Part II, (Hietanen), is a study of the mineralogy, petrology and metamorphism of the overthrust area in Lancaster County, with some discussion, based on reconnaissance work, of the same features in the Piedmont farther south.

Part III, (Hietanen), is a study of the metamorphism, structure and fabric of the Octoraro and Wissahickon schists in the neighborhood of Bryn Mawr, Pennsylvania.

A summary and discussion of conclusions by Cloos concludes the paper.

The type locality of the Martic overthrust, in southern Lancaster County, has been studied most thoroughly. The area was remapped in detail, critical areas were mapped by plane table methods, thousands of observations were made of the attitudes of all recognizable structural features, including bedding, cleavages, joints, lineations, and fold axes. Sixty oriented specimens were collected and their fabrics analyzed, and finally the petrofabric data were correlated with field data both by individual comparisons and statistical means. In order to examine the possibility of facies changes in the Cambrian formations of the area, the work was further supplemented by studies of the insoluble residues of about 500 specimens.

Cloos has presented evidence that appears entirely convincing that there is a five-fold stratigraphic repetition in the Martic area, and also

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, W. S. Bayley, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

that the structures now visible there—on all scales from that of the field map to that of the microscope slide—record but a single orogeny. The practically conclusive evidence of the existence of the Martic overthrust makes one wonder why the author put quotation marks around the name in the title of the paper. Perhaps this is to be explained as a reaction against the assumption that the existence of a thrust fault here necessarily implies a pre-Cambrian age for the Wissahickon schist. This, of course, is not the case, as, according to Cloos' interpretation, there are at least four lower thrusts in the area, each of which brings lower Cambrian rocks above Ordovician. It is thus entirely possible that the Wissahickon is in part of Cambrian age, as the author suggests; on the other hand, there is no evidence of compelling force that would justify the author's conclusion that, "the Wissahickon schist cannot be pre-Cambrian" (p. 191). It seems that the age of this puzzling formation has not in any way been established.

Cloos has shown that the thick series of rocks below the lowest known Cambrian of the South Mountain area has all its megascopic structures parallel to and hence probably of the same age as those in the adjacent Cambrian and nearby Ordovician. That this series is pre-Cambrian is, of course, not known, but its assignment to the Paleozoic would be fully as arbitrary as the frequently quoted assignment of the Wissahickon to the pre-Cambrian "because there is no evidence to the contrary." There are many regions where the unconformity between Cambrian and pre-Cambrian rocks is not strikingly angular, nor marked by thick conglomerates. The Belt series and overlying Cambrian of Montana and the Apache group and Cambrian of Arizona exemplify these relations. The recognition of such unconformities after even very mild dynamic metamorphism would be very difficult or even impossible. Hence it may be doubted that the rocks beneath the lowest recognized Cambrian of the South Mountain area may be safely put in the still lower Cambrian because no structural disconformity is recognized as yet. The granitic "sills" of these rocks find no counterparts in the adjacent known Paleozoic rocks and perhaps this difference should be assigned more weight than the author is willing to grant. At the same time, the author has shown that there are no stratigraphic evidences of facies changes that suggest that the Wissahickon in the Martic area is more probably Paleozoic. It seems, therefore, that the proper conclusion as to the age of the Wissahickon, on the basis of even this exhaustive study, should have been "unknown."

In view of the prodigious labor that the authors have already devoted to this work, it may seem ungrateful to ask for more. Nevertheless, it seems that, until structural and petrofabric studies are made of the Balti-

more gneiss of the Mine Ridge uplift and the persistence in it of relict fabrics differing in symmetry from those of the known Paleozoic rocks is demonstrated, the identity of structure in the Paleozoic and Wissahickon may be attributed to complete destruction of older vector patterns in one formation and overprinting in a later, post-Conestoga orogeny. The identity of fabric in these rocks may thus not be a very strong argument for a Paleozoic age of the Wissahickon, though it has certainly removed any structural argument that the Wissahickon is pre-Cambrian.

The above is a minor criticism of a paper that everyone interested in structural geology must read with profit. Cloos has discussed in a thorough and judicial way the structural data gathered on all scales and his critical analysis of the contributions of each part of the study to the synthesis of the structural history is illuminating and philosophical.

The admirable structural contribution of Cloos is supplemented by a petrologic study by Miss Hietanen. Her studies show that progressive metamorphism dominates all the rocks in southern Lancaster County and that isograds and metamorphic facies transgress all boundaries. There is no restriction of metamorphism to one formation and all the minerals found in the Wissahickon schist near the edge of the overthrust are also found in the Paleozoic Antietam schist. There are no signs of repeated metamorphism, as the mild chloritization found in a few places is probably hydrothermal and not confined to the Wissahickon. The metamorphism is clearly younger than the present structural disposition of the rocks. Although Miss Hietanen's conclusions seem to be in large part substantiated by her data, it is notable that her chlorite zone in the Martic area lies parallel to the overthrust boundary (Pl. 19). It is thus readily understandable how earlier workers may have mistaken such a local distribution as significant of retrograde metamorphism. This more detailed study seems to have eliminated this possibility, though not the overthrust. Several portions of Miss Hietanen's section suffer from confusion in expression, doubtless because the author was unable to examine the proofs.

The final section, on the area near Bryn Mawr, is devoted to the supposed extension of the Martic thrust to the east. Here Miss Hietanen finds the same relations as in Lancaster County, except that there is no stratigraphic evidence of the existence of a thrust. There is neither structural nor petrologic evidence of two orogenies, and all the structures in the Wissahickon are also present in the Conestoga limestone. If a thrust fault intervenes here, it must have been formed, as at Martic Forge, prior to the development of the close folding and recorded metamorphism of both formations. Here again, the study of the structures of the intervening gneiss might have thrown light on the persistence of relict structures through the post-Conestoga orogeny. In the interpretation of the

contact of the Octoraro and the underlying Conestoga, Miss Hietanen lays much stress on the gradation from carbonate rock with only a trifling amount of detrital material into schist with minor carbonate lenses, within a thickness of a few feet transverse to the contact. This gradation, in view of the lack of definite bedding in the exposures described, could equally well be interpreted as resulting from metamorphism of a friction breccia, for many fault breccias in less metamorphic terrains show similar transitions in composition; however, this is a captious criticism. The work clearly has removed any structural evidence of a thrust between the Conestoga and the Octoraro. If a thrust exists, it must be demonstrated on stratigraphic grounds, which has not yet been done.

The authors are to be congratulated on this work. They have abundantly justified their objective in contributing factual material to a final solution of this difficult problem. The paper is a work of great merit and marks a new and fruitful approach to one of the most puzzling structural questions in Appalachian geology.

JAMES GILLULY.[1]

UNIVERSITY OF CALIFORNIA, LOS ANGELES.

**Physics of the Earth—IX: Hydrology.** Edited by OSCAR E. MEINZER. Pp. 712. McGraw-Hill Book Company, Inc. New York and London, 1942. Price, $7.50.

This important book is the latest addition to the geophysical handbooks prepared under the direction of various committees of the National Research Council. Like its predecessors it is a symposium—in this case with 24 contributors—that constitutes an excellent basic reference work on the subject, each phase of which is dealt with by an expert. This kind of book helps to break down the bulkheads that separate the branches of science as commonly organized in research and teaching institutions, because it brings together in unified form discussions that usually appear separately in treatises on meteorology, geology, soil science, and engineering.

The symposium aims at tracing the physical-chemical controls and effects of water throughout the hydrologic cycle. An interesting introduction by the Editor discusses the scope of hydrology and its historical development from ancient times to the present. The chapters not immediately related to geology include Precipitation, Evaporation from free water surfaces, Snow, snow surveying, and ice, Infiltration, Transpiration and total evaporation, and Soil moisture. Those of more direct geologic import include Glaciers, Lakes, Ground water, Runoff, Droughts,

[1] Published with the permission of the Director, Geological Survey, U. S. Department of the Interior.

Physical changes produced by waters, Hydrology of limestone terranes, and Hydrology of volcanic terranes.

Some of the material included in these chapters is to be found in well-known handbooks, but much of it is collected from scattered, very specialized references and unpublished information. Put together by specialists and accompanied by carefully considered lists of references to the literature, the result is up-to-date, concisely presented information of high value, constituting a most useful "first reference" and a clear starting point for more detailed study of any branch of hydrology.

R. F. FLINT

**Chronic Pulmonary Disease in South Wales Coalminers.** I—Medical Studies. Special Report Series, No. 243, Medical Research Council, His Majesty's Stationery Office, London, 1942. Price, 10 s. 6 d.

The Welsh coal mines have in recent years shown a very high proportion of silicosis among the workers, at a rate 100 times as high as that occurring in English coal fields. Furthermore, in addition to these certified cases compensation has been claimed by many workers who had pulmonary disease but did not show evidence of classical silicosis. A special medical research council committee now reports as the result of an intensive study that many cases of lung disease among these workers are clearly due to dust inhalation even though pathological findings differ somewhat from those accepted in the past as diagnostic of silicosis.

The diseases in question are by no means limited to work in hard headings but affect all workers at the coal face and other handlers of the coal. The incidence of the disease in South Wales is closely correlated with the type of coal, being most serious in the northwest part of the beds where a very high grade of anthracite is produced and decreasing progressively towards the southeast where the coal deposits grade off to a typical bituminous area. No dust analyses are cited in the present report which would enable one to decide whether this incidence is directly related to silica content. The authors urge a control of dust by ventilation, mist projection, or water sprays; and regular periodic examination of the workers to detect early damage.

C.-E. A. WINSLOW

**Report of the Committee on Sedimentation, 1940–1941.** Mimeo. Pp. 110; Charts 2. Nat. Research Council, Washington, 1942. Price, $1.00.

The report of the Committee on Sedimentation of the Division of Geology and Geography of the National Research Council for the year 1940–1941 has recently been published. The work of this Committee is

to prepare summary reports of progress in different fields of sedimentation and to increase the fund of knowledge on special problems. The report this year contains 10 such articles. The most important of these is a set of two charts prepared by R. Dana Russell listing the physical properties of more than 150 minerals that are commonly found in sedimentary rocks. The data are arranged in a new order, which experience has shown enables students to determine minerals more rapidly than formerly. Every student of petrography will find these charts useful.

Another article of special interest is a report by F. J. Pettijohn on the present state of knowledge of quantitative studies of sedimentation. Two reports on diagenetic changes in sediments are included: one by W. P. Kelley on soils, and the other by Geo. A. Thiel on calcareous sediments. Other articles are: current literature on recent marine sediments by H. C. Stetson; research on sedimentation in the Soil Conservation Service by C. B. Brown; research in sedimentation in the Gulf Coast region by F. W. Rolshausen; the sediments of Lake Provo, Utah, by H. J. Bissell, and two papers on statistical compilations of quantitative data on sediments, one on alluvial gravels by W. C. Krumbein, and the other on Mississippi delta sediments by August Goldstein, Jr.

WALTER H. BUCHER

**Mines Register, 1942 Edition** (Successor to Mines Handbook). Pp. 742. Atlas Pub. Co., New York, June, 1942. Price, $15.00.

This volume 31 is timely with its description of 4,000 active mines, its list of 22,000 inactive mines, and the location of old mines being reopened, new ones being opened up, and present ones being expanded. The customary procedure is followed, listing the company, financial structure, production, equipment and officers. Active mines are listed geographically, and leading nonferrous mines throughout the world are also described. There is also a statistical section; lists of officers and directors of companies, equipment and security prices.

This volume is welcome to all the mining profession and its list of inactive mines will be scrutinized closely to search for potential producers.

## BOOKS RECEIVED.

WILLIAM E. BENSON.

**Radial Detection. A Guide to the Use of the Radial Detector, Miscalled the Divining Rod.** A. A. COOK. Angus and Robertson, Ltd., Sydney, 1941. Pp. 98. Price, 85 cents. *A discussion of the cause of the action of the divining rod when it is used in a proper manner, under proper conditions by a qualified operator. It is assumed that the instrument reacts to 'radiations' emitted by natural bodies attracted to the*

*operator and transmitted through his superficial nerve system to the earth. The qualifications of a successful operator are specific on the basis of the author's experiments and the proper conditions under which he must act are described.* W. S. B.

**Estudios Sismologicos.** M. CENTENO-GRAÜ. Litografia del Comercio, Caracas, Venezuela, 1940. Pp. 555; Maps, 2; Tables, 5. *Includes a complete catalog of all earthquakes occurring in Venezuela from 1530 to 1939; the relation of these to the geology and geography of Venezuela; studies of the general phenomena of earthquakes peculiar to these tropical regions; a study of the most effective "earthquake-proof" construction, together with a presentation of the author's "electrotectonic" hypothesis for the cause of earthquakes and his "laws of coincidences" for predicting future periods of danger.* B. B.

**Ecological Crop Geography.** KARL H. W. KLAGES. Pp. 615 + xviii; Figs. 108; Tables 66. The Macmillan Co., New York, 1942. Price, $4.50. *A book, primarily of interest to agronomists, divided into four sections: The social environment of crop plants; A generalized discussion of the physiological environment; Detailed discussion of ecological factors and the interactions of plants with these factors of their environment; Distribution of important crop plants. Geologists may be interested in chapters 11, 12 and 13 on moisture relationships and chapter 21 on soils.*

**Plane Table Notebook.** KENNETH K. LANDES. George Wahr, Pub., Ann Arbor, Michigan, 1942. Price, $1.00. *A compact 8" by 5" plane table notebook with abbreviated rules inside the front cover and plane table notes in a pocket of the inside back cover, with additional sheets for field notes.*

**U. S. Bureau of Mines. Metallurgical Division, Progress Reports.** Washington, May, 1942. No. 53. **Ore-Testing Studies,** Rept. Invest. 3629. *Results of tests on precious metals to provide information as to satisfactory method of treating the ore. Includes gold ore or tailings from North Carolina, Georgia, Nevada, Utah, Idaho, California and Oregon; gold-silver ore or tailings from Colorado, Nevada, and Wyoming; and complex base-metal ores containing gold and silver from Colorado, Idaho and California.*

No. 55. **Dry Differential Grinding Tests of Carnotite Ores,** Rept. Invest. 3636. *Results of tests for best method of recovering vanadium from carnotite ores from Colorado and Arizona.*

**Stemming in Metal Mines.** Firing Through Stemming, Rept. Invest. 3646. *Results showing safest and most practical way to handle a missed hole.*

**Canadian Mines Handbook, 1942.** Pp. 248. Northern Miner Press, Toronto, 1942. Price, $1.00. *Information compiled by the Northern Miner Press about the active mining companies of Canada with a listing of inactive companies.*

**The Diamond Industry in 1941.** S. H. BALL. Pp. 23. Jewelers' Circular-Keystone, New York, 1942. *The annual review of world mining, cutting and distribution of diamonds, including war influences.*

# SCIENTIFIC NOTES AND NEWS

L. C. GRATON, professor of mining geology at Harvard University, has been named to the Sturgis Hooper professorship, devoted to research. R. A. DALY, retiring Sturgis Hooper professor, was awarded the honorary degree of Doctor of Science by Harvard at the annual commencement.

The G. S. A. is preparing a directory of North American geologists, similar to the "Internationaler Geologen und Mineralogen Kalender" which has not been published since 1937. The directory will contain name, position and address of individuals as well as a list of geological departments and institutions and their personnel.

W. S. BURBANK of the U. S. Geological Survey and Secretary of the Economic Geology Publishing Co. is the representative of the S. E. G. on the Division of Geology and Geography of the National Research Council for 1942–43.

V. M. LOPEZ, director of the Geological Service of Venezuela, was recently made a member of the Venezuelan Academy of Sciences.

H. A. MEYERHOFF, professor of geology at Smith College, has been appointed mediator on the National War Labor Board.

G. V. COHEE has resigned from the Illinois State Geological Survey to become assistant state geologist of the Indiana Geological Survey.

R. S. DEAN, chief of the Metallurgical Division, U. S. Bureau of Mines, has been appointed assistant director of the Bureau.

T. A. DODGE has joined the geological department of the Cananea Consolidated Copper Co. in Cananea, Sonora, Mexico.

W. E. BENSON and J. D. STROBELL, graduate students in the department of geology at Yale University, have joined the U. S. Geological Survey for strategic mineral field work in Mississippi and Colorado, respectively.

JAMES SEMPLE has been appointed by the U. S. Bureau of Mines to investigate possible aluminum clay deposits in northern Idaho and eastern Washington.

E. L. PERRY of Williams College is the new chairman of the Eastern Section of the Seismological Society of America.